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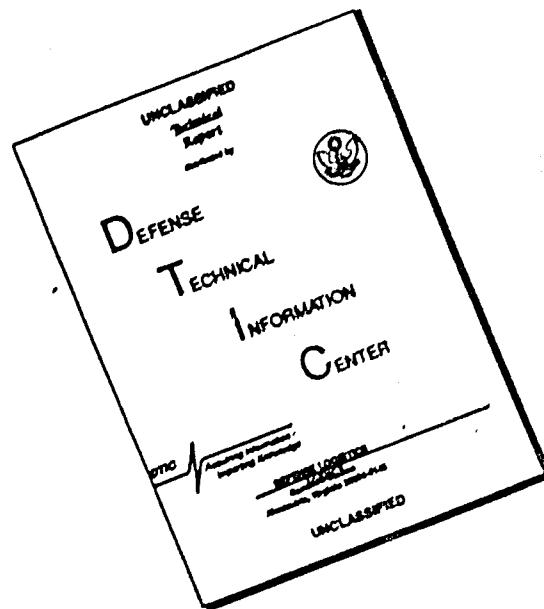
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STATIC LIFT CHARACTERISTICS OF JET SLOTS—

A CLARIFYING STUDY OF THE EXTERNAL EJECTOR
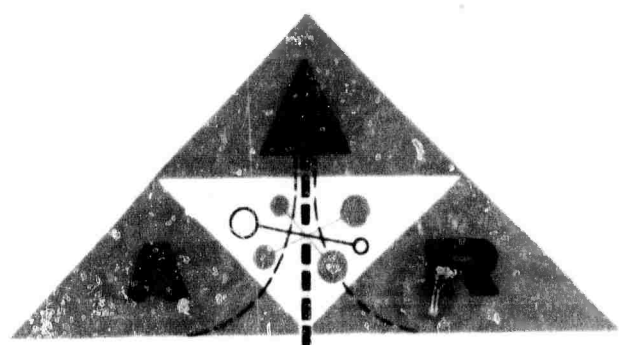
FINAL REPORT

ARD 213

Nonr 2428 (00)

Report No. ARD-213

15 October 1958

STATIC LIFT CHARACTERISTICS OF JET SLOTS -

A CLARIFYING STUDY OF THE EXTERNAL EJECTOR

FINAL REPORT - CONTRACT NO. Nonr 2428(00)

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ADVANCED RESEARCH

DIVISION OF HILLER AIRCRAFT CORPORATION

# 1. SUMMARY

The external ejector[*] utilizing a surface profile ~~developed by Cornell Aeronautical Laboratory~~ was evaluated in both two-dimensional and three-dimensional configurations for ~~the purpose of~~ defining the thrust augmentation potentialities ~~of this phenomenon in an attempt to end a controversy that has existed for a number of years.~~ The results ~~of the program, the recent work~~ of NACA and the almost ~~unanimous~~ conclusions of other reviewed ~~work~~ indicate that static thrust augmentation is not possible with the external ejector. ~~It was found however, that~~ ideal turning efficiencies as high as 88% are possible with this ~~extremely~~ simple hardware. In both two-dimensional and three-dimensional configurations, the turning efficiency increased with increasing nozzle slot height $(\sigma)$ which was terminated by breakaway in the two-dimensional tests and by insufficient air supply in the three-dimensional tests. Performance data and surface pressure surveys are presented for both configurations. Flow visualization by means of smoke streams is discussed.

[*] This name is used to describe the device that incorporates clinging flow over a surface and the accompanying external mixing. This device is sometimes called a "Coanda nozzle".

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## ACKNOWLEDGEMENTS

Mr. D. Whittley, Aerodynamicist, Special Projects Division, Avro Aircraft Ltd., Toronto, Ontario.

Dr. J. V. Foa, Professor of Aeronautical Engineering, Rensselaer Polytechnic Institute, Troy, New York.

Dr. K. T. Yen, Professor of Aeronautical Engineering, Rensselaer Polytechnic Institute, Troy, New York.

Dr. J. Logan, Ramo-Wooldridge Corporation, Los Angeles, California.

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Lt. J. R. Ramler, TRECOM, United States Army, Fort Eustis, Virginia

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Real Thrust Ratio   $\dfrac{\text{corrected resultant lift}}{\text{actual nozzle thrust}}$   $\left(\dfrac{F_R}{\dot{w}\sqrt{\Theta_4}} \bigg/ \dfrac{F_{nozzle}}{\dot{w}\sqrt{\Theta_4}}\right)$

Ideal Thrust Ratio   $\dfrac{\text{corrected resultant lift}}{\text{isentropic nozzle thrust}}$   $\left(\dfrac{F_R}{\dot{w}\sqrt{\Theta_4}} \bigg/ \dfrac{F_{isentropic}}{\dot{w}\sqrt{\Theta_4}}\right)$

$C_p$    specific heat at constant pressure, $\dfrac{\text{BTU}}{\text{lb }^{o}\text{R}}$

$F$    reaction, lb

$g$    gravitational constant, $ft/sec^2$

$h$    design slot height, in.

$J$    mechanical equivalent of heat, 778 ft-lb/BTU

$P$    absolute pressure, in. Hg

$T$    absolute air temperature, $^{o}$R

$V$    local air speed, ft/sec

$\dot{w}$    flow rate, lb/sec

$\gamma$    ratio of specific heats (1.4 used here)

$\delta$    $\dfrac{P_o}{P_{o_{SL}}} = \dfrac{P_o}{29.92}$    dimensionless ambient pressure correction

$\Theta$    $\dfrac{T_t}{T_{o_{SL}}} = \dfrac{T_t}{520}$    dimensionless ambient supply air temperature correction

$\sigma$    $\dfrac{\tau}{h}$    dimensionless nozzle height

$\tau$    test nozzle height, in.

## Subscripts

H       horizontal

o       ambient

SL     sea level

R       resultant

s       static

t       total

V       vertical

4       immediately upstream of external ejector

5       exit of external ejector nozzle and downstream along surface

## Superscripts

21     static surface pressure tap location

## 2.    INTRODUCTION

Historically, aircraft with vertical flight and hovering capabilities
came into being only when combined powerplant and lifting devices were
developed with ratios of thrust (or lift) to weight greater than unity.
The most successful aircraft of this type has been the rotary wing con-
figuration; unfortunately, this configuration is characterized by very
high operational costs that stem from the maintenance of complex rotor
and drive systems.  A second limiting characteristic of rotary wing air-
craft is its low forward flight speed.  These limitations have been im-
portant factors in encouraging the search for simpler and cheaper aircraft
that have the capability of hovering flight as well as high forward speed.

Turbojet engines with installed thrust-to-weight ratios as high as eight
are operational, and it is obvious that ways should be sought to utilize
the low specific weight characteristic of modern turbo-machinery for a
simpler, cheaper, and faster VTOL aircraft.  However, the high jet velocity
and relatively low mass flow of the turbojet makes vertical lift very in-
efficient by this means, as the most efficient hovering and vertical lift
configurations are those that provide a very small acceleration to a large
mass of air.  This concept of hovering efficiency is developed from the
fact that, although lift is equal to the change of momentum imparted to the
air by the aircraft, the power required is proportional to the square of
the wake velocity.  On this basis, a comparison of all known configurations
for hovering flight is made in Section III-A of Reference 1, which ranks
helicopter rotors with low disk loadings as the most efficient hovering

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devices, and direct lift with turbojets and rockets as the least efficient in spite of the exceptionally low specific weight of the pure jets.

These considerations lead to a search for ways to augment the static lift (thrust) of a pure jet with such devices as ejectors, or by utilizing the tendency of flow to cling to a surface. In the case of jet ejectors, the mass flow rate is increased by internally mixing secondary air with the primary jet. In the case of the clinging flow phenomenon, there is an "external ejector" action, with the jet attaching to an external surface and mixing with ambient (secondary) air, possibly resulting in a net increase in momentum. These features are also discussed in Reference 1, Sections IV-A-f-a and-b respectively.

In the case of the external ejector, it was thought that external mixing with ambient air would open up the possibility of using surfaces for lift that are necessary in any event to enclose the aircraft components. Also some of the problems and deficiencies of a concentrated jet might possibly be avoided by spreading the jet over the aircraft exterior and using its energy to reduce pressure over the upper surface of the aircraft. General layouts of aircraft that might utilize this feature are shown in Figures 7 and 8 of Reference 2.

The state-of-the-art with reference to the clinging-flow phenomenon was not well documented, and the subject has been a controversial one. At the time this study was begun, there was a paucity of agreement in the experimental evidence concerning this surface lift effect, and what data did exist was far from conclusive. The earliest recorded interest in the tendency of a

flow to cling to a surface is the work of M. Lafay in 1918 on the Chilowsky effect, as discussed in Appendix B. Another early experimenter was M. Henri Coanda, a Roumanian, who proposed to use the phenomenon in a variety of devices. Coanda's proposals were based on this discovery: if air is ejected from a rectangular or annular slot or nozzle, and if a series of surfaces are attached at increasing angles from the initial axis of flow, there is an increase in the velocity and mass flow of the fluid, and the fluid tends to follow around the surfaces while entraining adjacent free air (Reference 3). The basic function is illustrated by a rectangular jet that is directed parallel and adjacent to a flat surface that sharply inter-sects another flat surface at an angle of about 30 degrees. The jet tends to break away from the angled surface, and this causes a pressure drop over it, which in turn causes the jet to be deflected towards the angled surface. By using a series of such flat surfaces, each at about 30 degrees or less to the preceding one, the jet can be made to deflect through angles as high as 180 degrees. Coanda believed that the sharp intersection of the surfaces enhanced the deflective action.

The clinging flow phenomenon was verified experimentally at Purdue University in 1948 by Boyer (Reference 4) and by Marwood in 1949 (Reference 5) under sponsorship of the USAF. Relationships of various parameters such as nozzle overhang, pressure ratio, width of jet, deflection angle, etc., were deter-mined. However, no experiments employing three-dimensional models were con-ducted, nor was the amount of lift determined.

Experiments were conducted at Cornell Aeronautical Laboratory with two-

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dimensional tests of flow over smoothly curving surfaces (Reference 6).
Thrusts were measured normal to the jet and found to be 1.7 times as high
as the thrust measured in the direction of the nozzle axis and with the
surface removed.  This augmentation ratio was obtained with side plates
(required for the augmented jet in the two-dimensional tests) left on
during the measurement of the jet thrust with the curved surface removed.
When the jet thrust was measured without the side plates, the comparison
showed very little augmentation.  It was pointed out that the side plates
caused a large loss (40%) in the basic jet performance.  It was reasoned
that elimination of the side plates by use of a high aspect ratio nozzle
or an annular configuration would result in a device of high augmentation.
It was discovered that the introduction of a "bump" into the jet (Figure 1)
improved the tendency of a fluid to cling to the surface.

The first theoretical analysis of the Coanda effect was accomplished in
1939 by Metral (Reference 7) for a perfect fluid and a single sharp-edged
bend.  This analysis indicated that the mass flow rate can be increased
considerably.  In a later analysis dated July 1955, Yen (Reference 8,
page 1) cast doubt on the practical value of the sharp-edged device on
the basis that, "...the theoretical flow pattern for a perfect fluid
around a sharp edge can never be realized in a real fluid with viscosity.
The boundary layer builds up at a rapid rate and separation occurs as a
result of the large pressure gradient downstream from the sharp edge".
Yen extended Metral's work to the case where the sharp edge is smoothed
out with a rounded corner.  Using the method of hodograph transformation
(based on the assumption of a perfect fluid) Yen indicated that, in general,

the increase of mass flow rate is reduced by the substitution of the rounded corner for the sharp edge.  Although Yen considered that, "An analytical investigation of the Coanda effect considering the viscosity of the fluid is very difficult and seems to be out of the question..." he did indicate that "...a qualitative analysis shows that the Coanda effect is seriously limited by the viscous effect of the fluid.  Consequently, unless effective and accurate boundary layer control techniques can be devised and applied, the practical value of the 'Coanda nozzle' appears to be doubtful."  (Reference 8, page 2).

An earlier work using a somewhat similar approach was published by Lighthill in 1945 (Reference 9).  Lighthill studied the tendency of a flow to cling to a smoothly curving surface and applied this tendency to the shaping of bends in wind tunnels.

A further brief theoretical analysis concerned with thrust augmentation of jets by von Karman to explain the superior performance claimed by Coanda for his internal ejector (Reference 10) predicts a superior augmentation for ejectors when the primary fluid is injected along the wall of the tube rather than from a centrally located nozzle.  von Karman suggests that this is most likely to be the reason for the good entrainment characteristics of annular internal jet ejectors rather than any "mysterious flow of the fluid around sharp edges" (referring to an ejector designed by Coanda).  He bases this suggestion on the likelihood that a greater lack of uniformity of fluid velocity will occur at the beginning of the mixing region when the primary jet is injected along a wall.  This lack of uniformity of fluid velocity

at the start of mixing is shown to be a vital element in ejector thrust augmentation.

An analytical investigation of the Coanda effect was made by Voedisch (Reference 3) in 1947 for the USAF. Voedisch also traced the history of Coanda's efforts to use the phenomenon for various devices, e. g., an induced flow (thrust augmentation) device, a wing for high-lift, low-drag characteristics, an exhaust scavenger, a wind tunnel fan, a water propulsion device, and a rotating pump. Of these, only the ideas for the exhaust scavenger and the induced flow device were successfully applied. The latter was used by Chasson, a radiator manufacturer, to induce air flow through a radiator by directing the exhaust gas from the engine through annular Coanda slots. The general manager of the firm, J. L. Poitrine, said that tests indicated a flow augmentation of about 6:1 with a nozzle 150 mm in diameter and 0.1 mm Coanda slot.

Voedisch concluded that the Coanda phenomenon consists of the following individual effects:

"1. An increase in the mass flow and velocity of a fluid issuing from the exit section of a rectangular or annular nozzle or slot by placing one side of the exit wall at an acute angle to the direction of initial flow, aided possibly by a straight extension of the other wall. The configuration of the two walls forms an off-set divergent nozzle.

"2. Deflection of the mass flow through an angle, by means of a series of surfaces at acute angles to each other. The deflection

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of a fluid by means of a smoothly curved wall is well known, and
various simple and useful applications can be cited and experiments
made to show this. By the use of steps, such as in the Coanda device,
it is plausible that the total angle of deflection may be greater,
since by the use of a sharp corner, such as is formed by two of the
surfaces, the mass flow is strongly accelerated, and the slight
separation causes a turbulence which produces an augmented mixing,
and a renewed boundary layer energy. It might be better to use a
smoothly curved surface until just before separation would normally
occur, and then, by means of a corner, renew the boundary layer
energy and allow a greater deflection.

"3. Entrainment of additional air by dragging the stationary air
along with the primary jet, providing an additional mass flow. It
is well known that a jet of any fluid has the property at its sur-
face to drag stationary fluid into motion by means of frictional
forces. Compared to a free jet, which can cause entrainment on all
sides, the Coanda device, due to the required contact of one side
of the jet with the wall, can entrain fluid along only one side.

"The Coanda device has inherent energy losses, which are produced
by the action of the device, as follows:

"1. Loss due to friction along the series of surfaces while a
change in the direction of motion of a fluid occurs.

"2. Loss due to boundary layer energy renewal." (Reference 3,
pages 2-3)

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It was on the basis of this background and in the belief that it was possible to achieve an augmentation of thrust by use of the external ejector that this program was begun. However, since this belief was based on test data which had not been verified, it was thought prudent to begin this investigation by verifying the most reliable of the previous work done on this phenomenon.

## 3. DISCUSSION

The test program began by evaluating an external ejector patterned after
a configuration conceived by Drs. Foa and Logan (Reference 6) at Cornell
Aeronautical Laboratory. Drs. Foa and Logan evaluated two families of
such surfaces, each described by a cubic equation in which the constants
are expressed in terms of the nozzle slot height. The best surface re-
sulting from this Cornell Aeronautical Laboratory work was used in the
large-scale Hiller tests. The profile of the surface which is described
by the equation

$$y = \frac{.2672}{h} x^2 - \frac{.075}{h^2} x^3$$

is shown in Figure 1. The test setup and procedures are described in
Appendix I.

### 3.1 Two-Dimensional Configuration*

The two-dimensional model was simply constructed of formica-covered ply-
wood side plates (one plexiglass side plate was used for flow visualization
tests) into which matching curved grooves (described by the equation in
paragraph 3.0) were routed to receive the aluminum surface. The top sur-
face of the nozzle upstream of the surface was hinged to allow testing at
nozzle heights other than the design nozzle heights. All joints in the
model were airtight. Figures 2 and 2A show the two-dimensional model.

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*It is recognized that the two-dimensionality of this configuration is open
to some question due to the finite size of the end plates and to viscous
effects.

The data obtained from tests of the two-dimensional configuration is presented in Figures 3 through 11. Examination of the figures shows that no thrust augmentation was found, contrary to the test results of the Cornell Aeronautical Laboratory work and the word-of-mouth reports of Coanda's work, which were claims of augmentation ratios as great as four to one. Recent discussions with Coanda (Reference 11) indicate that he still claims static augmentation for the external ejector, but the amount was not determined. The data is presented for various values of nozzle slot height in terms of $\sigma$, which is test nozzle height, $\tau$ , divided by the design height h.

Examination of the performance data (Figures 3 through 7) indicates that the ideal thrust ratio $\left( \dfrac{\text{corrected resultant lift}}{\text{isentropic thrust}} \right)$ increased with an increasing $\sigma$; 0.76 for $\sigma = 2/3$ to approximately 0.88 for $\sigma = 2$. This increase in performance is apparently due to the increase in hydraulic radius which is directly proportional to $\sigma$ rather than to any ejector characteristics. The increase in performance with increasing $\sigma$ is contrary to basic internal ejector theory and experiment which show that ideal thrust ratio increases with increasing values of area ratio (secondary area to primary area), i. e., decreasing $\sigma$. This is one indication that the flow phenomenon in the external ejector does not meet the requirements for achieving thrust augmentation. A requirement which is not met is that of low pressure in the mixing zone. The maximum performance occurs just prior to separation when the flow is unstable, as noted by vibration of the model. Boyer (Reference 4) also noticed that the force required to restrain the flat ?  lection surface was greatest when separation was imminent.

The centrifugal force of primary air flowing around the "corner" produces a suction pressure at the "corner" (lifting surface) of the external ejector to hold this fluid stream to the surface of the model. The pressure distributions (Figures 9 through 11) indicate that the magnitude of this suction pressure is directly proportional to $\sigma$ for the range of supply pressure and $\sigma$ tested. Figure 12 shows location of the pressure taps.

Evaluation was stopped at $\sigma = 2$, because at $\sigma = 2$ and greater it was necessary to artifically "attach" the flow to the model surface; also, the supply pressure at which flow separated from the model surface became lower. Figure 13 shows the supply pressure at which breakaway occurs and the depression at the crest just prior to breakaway. It can be seen from this plot that breakaway with $\sigma = 2$ occurs when super-velocities approach Mach 1 at the crest. Initially it was believed that the breakaway was due to adverse pressure gradient resulting from a compression shock on the surface similar to that occurring on the wing of an aircraft when the critical Mach number is reached.

The suddenness of the separation phenomenon supported this theory, as it was found during testing that the flow, with increasing supply pressure, was either completely attached (deflected approximately $90^{o}$) or separated (deflected approximately $5^{o}$). However, further testing at other $\sigma$'s disproved this theory. Static pressure surveys along the surface indicated that the adverse pressure gradient downstream of the crest increased as $\sigma$ was increased. No reverse flow was evident during the onset of detachment. Figure 13 shows that supercritical pressure ratios were reached. It was

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also noted that the flow reattached at reduced supply pressure after separation at $\sigma$'s that did not require artificial attachment in the first place ($\sigma$ up to approximately 1.88). This reattachment occurred at a supply pressure of approximately 0.5 inch of mercury. At $\sigma$ = 1.47 it was found to be impossible to cause separation by increasing the supply pressure within the limits of our supply system. Figure 13 shows that a supercritical pressure ratio of approximately 3.0 was attained at the crest at $\sigma$ = 1.47 with a supply pressure $(P_{4_t} - P_o)$ at about 13 inches of mercury. Metral and Zerner (Reference 12) point out one use of this phenomenon as an inexpensive source of supersonic flow.

At $\sigma$'s where artificial attachment was initially required ($\sigma >$ approximately 1.68) it was found that the deflection also increased as the supply pressure was decreased after separation did occur, but did not increase sufficiently to cause reattachment.

The separation phenomenon was found to be unpredictable. That is, at a fixed value of $\sigma$ = 2 the supply pressure at which separation occurred was found to vary from 5.1 to 7.1 inches Hg. The cause of this variation was not determined. The basic cause of separation was not determined.

In an attempt to learn more of the phenomenon, flow visualization tests were made with small scale models and a low-pressure air source, which permitted hand manipulation of the model and air source. Both a flat plate model (Figure 14) and a model approximating the full-scale model were used. Figure 14 shows the flat plate model with smoke in the primary

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jet for visualization purposes. It was found with the flat plate model
that reverse flow (fixed vortex) existed between the jet and surface
even when the flow was attached and the deflection was small. Fluid in-
jected through small holes (static pressure taps) in the flat surface
continued to indicate reversed flow right up to the sharp corner of the
surface and nozzle exit even after it was no longer visible to the naked
eye as the deflection angle of the plate was decreased. This vortex grew
in size as the deflection angle increased until separation occurred at
approximately $45^{\circ}$. Reattachment occurred when the deflection angle was
reduced to approximately $30^{\circ}$. It was noted that the flow clung closer
to the surface of the model approximating the profile in Figure 1 than
to the flat plate model. The total deflection was approximately doubled
by use of the model approximating Figure 1. No reverse flow was noted.

Figure 15 shows flow over a sharp corner, as was shown in Figure 14, but
without side plates. Breakaway occurred at a lower deflection angle $\approx 35^{\circ}$.
In the middle photograph of Figure 15 the jet is shown just after separation.
The lower photograph shows the smoke trace on the flat deflection surface.
It is interesting to note that the edges of the jet at the nozzle exit
appear to be more tightly attached than the center. Also, some of the
flow at the edges (at the nozzle exit) appears to rotate inward and upstream
back to the center of the nozzle exit. The jet can also be seen to contract
in width due to lower-than-ambient internal pressures. Boyer concluded
(Reference 4) that clinging flow was only a two-dimensional phenomenon, and
that a nozzle and surface of infinite width were required for clinging to
exist without benefit of side plates. His observation was based on a

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nozzle aspect ratio equal to 2. The nozzle used in these small scale tests had an aspect ratio of 15. It should also be pointed out that the smoke trace on the flat surface with side plates did not indicate any flow across the surface.

Limited flow visualization tests were conducted with the f²⁻ -scale model in an attempt to better understand the flow breakaway phenomenon and to visually comprehend the vigorousness of entrainment of the secondary air. Little success was realized in the attempt to understand this separation phenomenon. However, considerable success was achieved in obtaining a visual appreciation of the magnitude of entrainment. It was noted that inflow of secondary air in the region of the horizontal portion of the surface was sluggish in comparison with inflow in the region of the vertical portion of the surface. That is, inflow velocity increased in the downstream direction relative to the primary flow. A view across the surface (i. e., parallel to surface and normal to primary flow) indicated that secondary flow did not mix with the primary flow sufficiently to reach the surface until approximately $2\tau$ downstream of the surface crest, or $4.5\tau$ from the nozzle outlet. Data obtained on a jet sheet ejected along a straight wall (Reference 13) indicated the jet core begins to dissipate at about 8 to $10\tau$ downstream from the nozzle. However, Caille (Reference 14) found that when the wall was curved, the dissipation rate was increased two to three times. He attributed jet dissipation to secondary air mixing. This data would tend to support the rapid jet penetration noted in the present tests. Figures 16 and 17 show a trace of this smoke-defined secondary flow on the side plate with $\sigma = 2$ (trace caused by the smoke

condensing on side plates) which is identical with the view described above. Figure 18 shows traces of both the attached and separated flows.

A flat sheet was hand held between the side plates (Figure 19) so as to form a rectangular duct with the vertical portion of the surface, thereby roughly simulating the mixing zone of an internal flow ejector. It was qualitatively noted that the inflow over the horizontal portion of the surface was considerably more vigorous than in the previous case. This rectangular duct provides a "sealed" area to permit low pressure mixing that is considered essential by B. S. Stratford (Reference 15) and others for achieving augmentation. It also serves to direct the inflow so that it can be "felt" by lift-producing surfaces. Unfortunately, it was not possible to measure the resulting reaction with this configuration.

Dr. Logan, who had assisted Dr. Foa at Cornell Aeronautical Laboratory, indicated through correspondence that he thought the difference between our work and Foa's and his at Cornell Aeronautical Laboratory might possibly be due to the difference in side plates (Hiller tests used less side plate). Brief tests were conducted to check this. Side plate area was increased approximately three-fold by temporarily placing additional formica panels around the original and taping the joints. Figure 22 shows the outside of a model with enlarged side plate. No effect on performance was noted.

Since we were unable to verify Cornell Aeronautical Laboratory results and also unable to obtain verification of any augmentation, it was believed advisable to discuss the problem with other current investigators of the

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external ejector and to contact Cornell Aeronautical Laboratory for a possible clue as to the cause of the discrepancy between our respective results. Uwe H. von Glahn's work at NACA, Cleveland was brought to our attention through his article in the SAE Journal, "Jet-Deflection Devices". Reporting of their work on the external ejector was very general, and, since the NACA report covering the effort had not been published, a visit was advisable. Also visited on the trip were Avro Aircraft Company (currently engaged in external ejector investigations), Cornell Aeronautical Laboratory, and Dr. Foa at Rensselaer Polytechnic Institute. In general it was found that none of these current experimenters (NACA and Avro) had achieved thrust augmentation (i. e., ideal thrust ratio $>1$) through use of the two-dimensional external ejector in either flat or curved plate configurations. Details of these conferences are presented in Appendix II.

Brief tests were made in ground effect for the purpose of determining the ground effect and also to learn if ground effect could have possibly been the cause of the discrepancy between our results and those of the Cornell Aeronautical Laboratory. The procedure is discussed in Appendix I. The results of these tests are shown in Figures 20 and 21. Note that the ground effect has negligible effect on the vertical (lift) reaction, but that it approximately triples the horizontal (thrust) reaction. The resultant reaction in ground effect is approximately 3% greater than the resultant reaction out of ground effect. The resulting ideal thrust ratio is 0.90, and the real thrust ratio $\left( \dfrac{\text{corrected resultant lift}}{\text{actual nozzle thrust}} \right)$ 0.92. The real thrust ratio obtained by Cornell Aeronautical Laboratory was 1.05 for this particular surface profile (Reference 6). In these tests, ground

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clearance between the end of the model surface and the ground plate was equal to approximately $2\tau$.

Another test was conducted at the same ground clearance but with the ground plate supported by scales. This produced a greater vertical reaction than had been measured on the model in the duplicate test above. It is believed that this greater reaction is due to some additional "ground" effect on the ground plate such as could have resulted from a vertical surface which was possibly close enough to turn the jet vertically upward (that is, prevent unrestricted horizontal spreading) within the influence of the ground board. It is believed that a similar condition in the Cornell Aeronautical Laboratory set-up could possibly be the cause of the discrepancy between our work and theirs, as all of their thrust measurements were made with a thrust (ground) plate.[*]

It was our conclusion at this point that, based on the two-dimensional tests and the results of other investigators, it is not possible to achieve thrust augmentation with an external ejector. However, it was felt appropriate by both ourselves and the Office of Naval Research project officer to evaluate the three-dimensional configuration of the external ejector in order to attempt to end the thrust augmentation controversy.

[*]Recent personal correspondence with Lt. J. R. Ramler of TRECOM points out that recent tests sponsored by TRECOM at the Naval Research Laboratory to evaluate the external ejector with a pulsejet as the primary jet source have not shown any augmentation.

## 3.2    Three-Dimensional Configuration

This model has a surface profile which is described by the same equation as the two-dimensional model.  However, the nozzle aspect ratio of this model at the design nozzle height is 75.5 or approximately 3.1 times that of the two-dimensional model.  It was believed that this increase in aspect ratio resulting in a thinner primary sheet and an increased area ratio of mixing surface to jet exit area would cause an increase in performance if the entrainment of secondary air was important to performance of this external ejector.

It was also reasoned that the additional degree of freedom by expansion of the primary jet in the radial direction would result in a lower internal jet pressure and greater entrainment and consequently improved performance.

This model, of which the outer surface was "turned" from wood, is shown in Figures 23, 24, and 25.  The position of the nozzle cap which is supported by the center spindle can be varied to permit different values of $\sigma$.  The center spindle is supported by three struts from the steel duct.  The model was carefully constructed to insure that the nozzle exit height would be constant around its periphery.  The data obtained from this model is presented in Figures 26 through 31.

It was found that there was insignificant difference in maximum performance between the three-dimensional case and the two-dimensional case.  Examination of the performance curves (Figures 26 through 29) shows that the ideal thrust ratio increases from 0.8 at $\sigma = 3/4$ to 0.87 at $\sigma = 2$.  At a fixed value of $\sigma$, the ideal thrust ratio increases slightly with increasing supply pressure.

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The primary difference in the characteristics of the two different models occured in the breakaway phenomenon. It was found however that it was not possible to cause the flow to breakaway from the surface by increasing the supply pressure at the larger $\sigma$ even though the flow initially had to be artificially attached (by reducing $\sigma$ to approximately 1 and then increasing $\sigma$ back to test value) to start the test. This inability to cause breakaway may not necessarily be due to the three-dimensionality of the configuration, which eliminates possible end plate interference, but rather to the cap configuration (Figure 25) which would tend to turn the primary air more than $90^{\circ}$ at the large $\sigma$'s where breakaway occured in the two-dimensional case.

Observation of the surface static pressures support this contention. At the particular condition observed, $\sigma = 2.7$, $(P_{4_t} - P_o = 2)$ the depression at station 8 became equal to that at station 7 (refer to Figure 25 for station location). As $\sigma$ was increased, the depression at station 8 exceeded that at station 7. In the normal flow regime ($\sigma = 0$ to 2.7) the greatest depression always occurs at station 7.

The static surface pressure surveys for the three-dimensional configurations are presented in Figures 30 and 31. It will be noted that the maximum pressure coefficient is less than that obtained with the two-dimensional external ejector. At $\sigma = 1$ the pressure coefficient is approximately 63.0% of the two-dimensional case and at $\sigma = 2$ approximately 57% of the two-dimensional case. This reduction is partially attributed to the reduction in primary sheet thickness at the crest due to radial expansion that exists

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with the three-dimensional configuration. It can be seen that the base

pressure (stations 24 and 25) was essentially equal to the ambient pressure,

that is, the pressure coefficient was less than 0.001. Surface pressures

were also measured around the circumference (dash-numbered stations, see

Figure 25) at three stations to check the uniformity of the flow. The

data shows some variation in the flow around the circumference but varia-

tion is not of large magnitude.

A series of frames selected from the motion pictures taken of the flow

visualization tests on the three-dimensional external ejector are presented

in Figure 32. The frames were selected at five-frame intervals. This film

was taken at 64 pictures per second using available light and Kodachrome

film. Hexachlorethane smoke grenades were used for the smoke source. In

this series of photos $\sigma = 1$, the supply pressure $(P_{4_t} - P_o) = 11.0$. in. Hg.

It is difficult to appraise the differences in the inflow velocity from

these figures, but actual observation of the test and study of the motion

pictures indicate an increase in the inflow velocity as distance from the

nozzle exit (along the surface) increased. This was not a great increase

in velocity. It can be readily seen that the inflow is normal to the

primary flow as noted by other investigators of free jet phenomena and in

some instances appears to enter at an angle greater than $90^o$. Close in-

spection of Figure 32-1 reveals the primary jet flow over the crest is

uncontaminated by the secondary flow. Figure 33 shows the smoke trace on

the model.      can be seen that the secondary flow does not penetrate the

primary flow until approximately 4.5 to 5τ downstream from the nozzle exit.

20

Both these observations are identical to the situation discussed for the two-dimensional case.

## 4.    CONCLUSIONS

The primary conclusion reached in the present experiments, the recent results of NACA, and the almost unanimous conclusions of all other reviewed work indicate that static thrust augmentation is not possible with the external ejector.

Secondary findings indicate the following:

A.  High turning efficiencies can be simply realized.

B.  Supersonic velocities can be inexpensively achieved.

C.  Ground effect on the two-dimensional configuration has negligible effect on the vertical lift realized from an external ejector, but increases the horizontal thrust by a factor of three.

D.  Flow visualization tests indicate the inflow is not vigorous and is normal to the primary flow.

E.  The breakaway phenomenon requires additional study for proper and complete understanding.

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$$y = \frac{.2672}{h} x^2 - \frac{.075}{h^2} x^3$$

Note: In this figure, lower portion of curve is omitted for simplicity
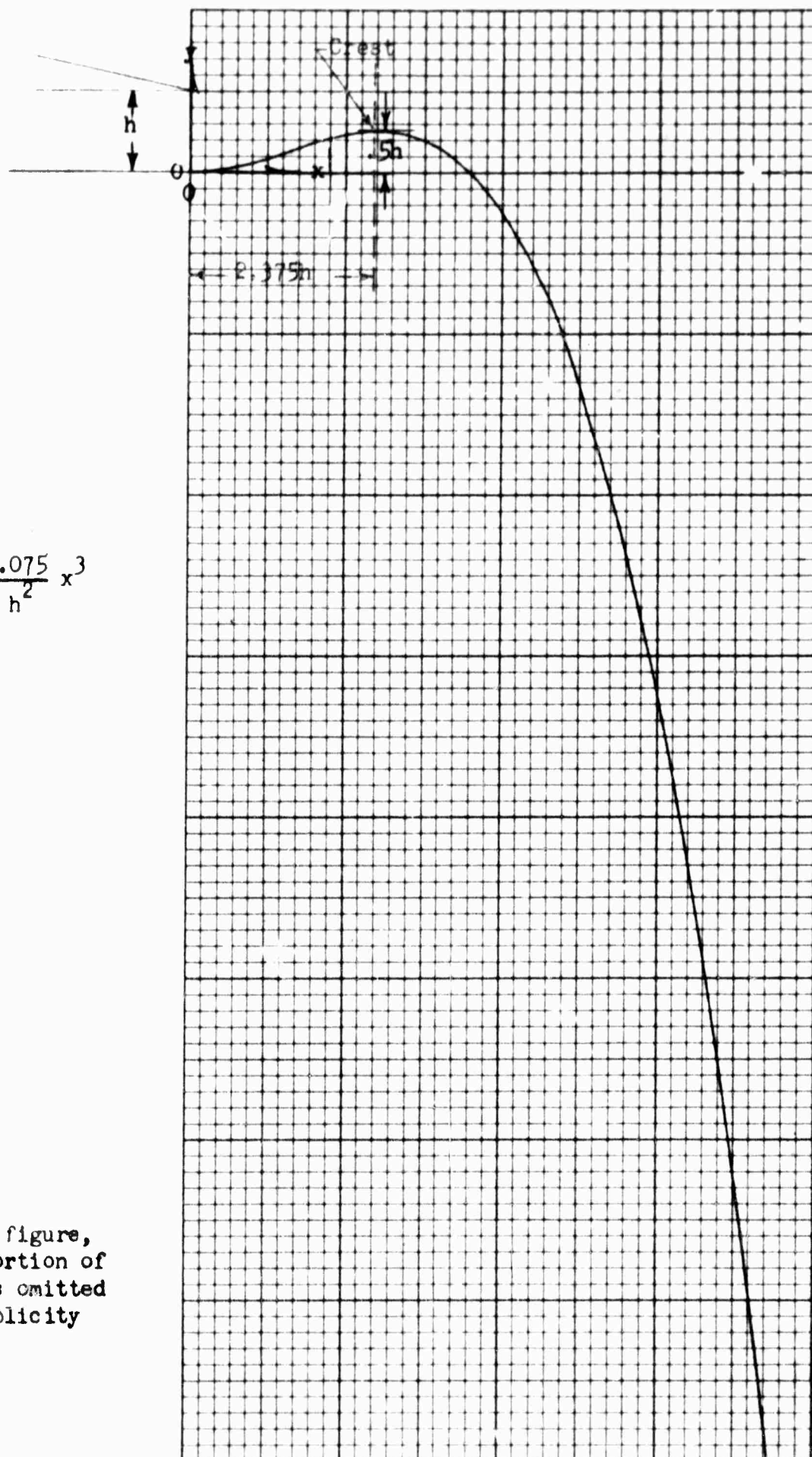
FIGURE 1 : TYPICAL SURFACE PROFILE
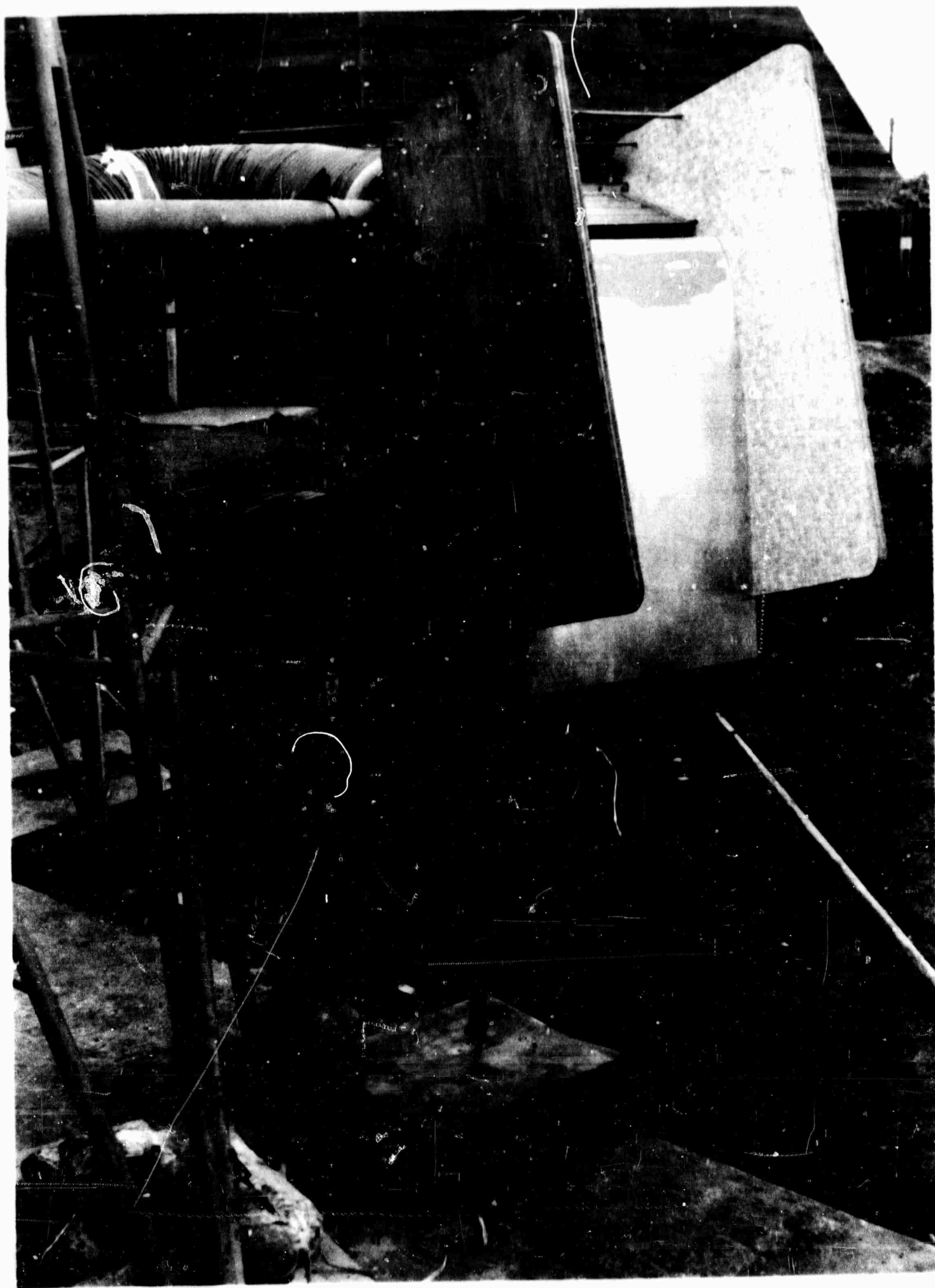
FIGURE 2: TWO-DIMENSIONAL EXTERNAL EJECTOR INSTALLED ON TEST STAND
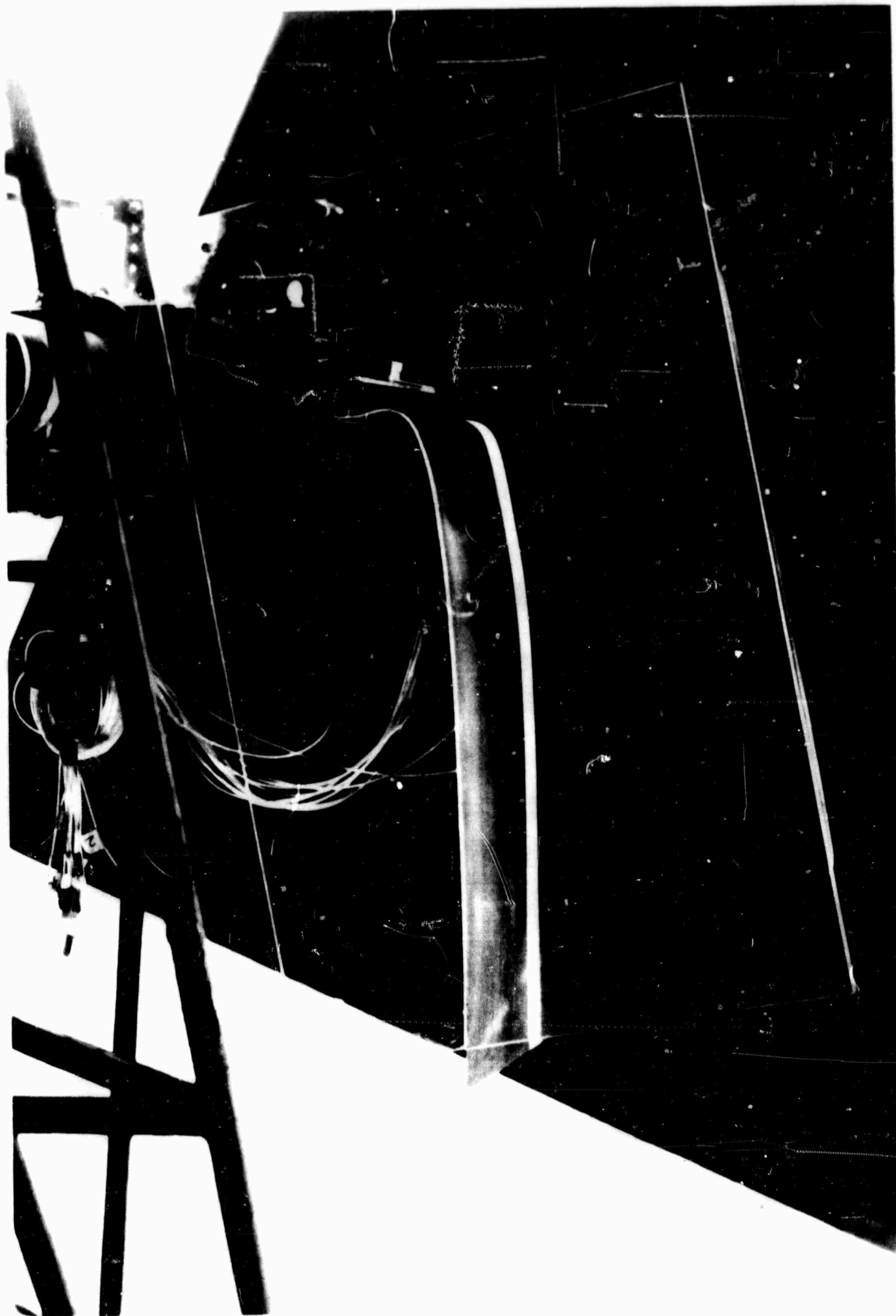
FIGURE 2A: TWO-DIMENSIONAL EXTERNAL EJECTOR INSTALLED ON TEST STAND WITH TRANSPARENT SIDE PLATE
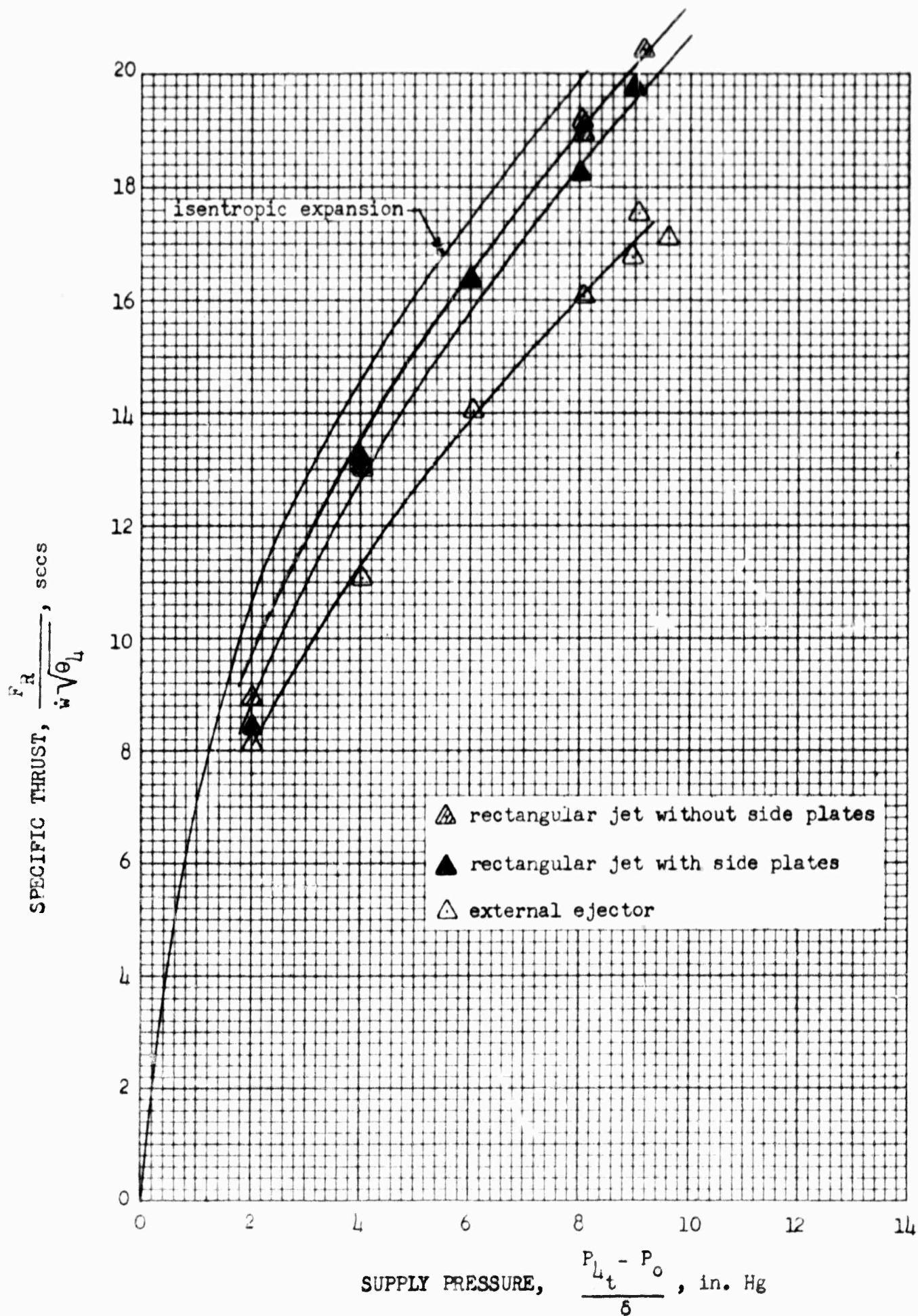
FIGURE 3: STATIC PERFORMANCE OF TWO-DIMENSIONAL
EXTERNAL EJECTOR AT σ = 2/3
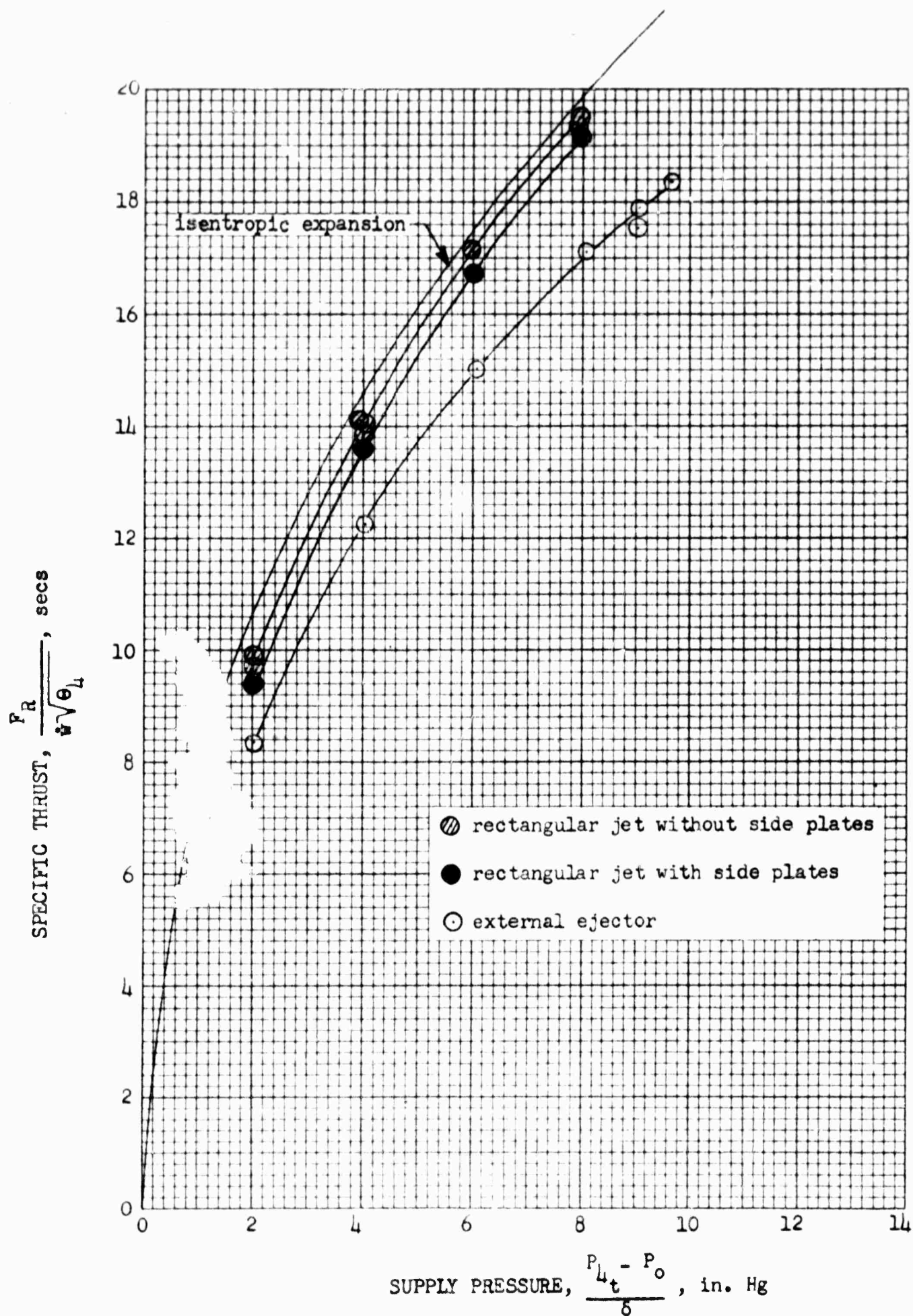
FIGURE 4: STATIC PERFORMANCE OF TWO-DIMENSIONAL
EXTERNAL EJECTOR AT $\sigma = 1$
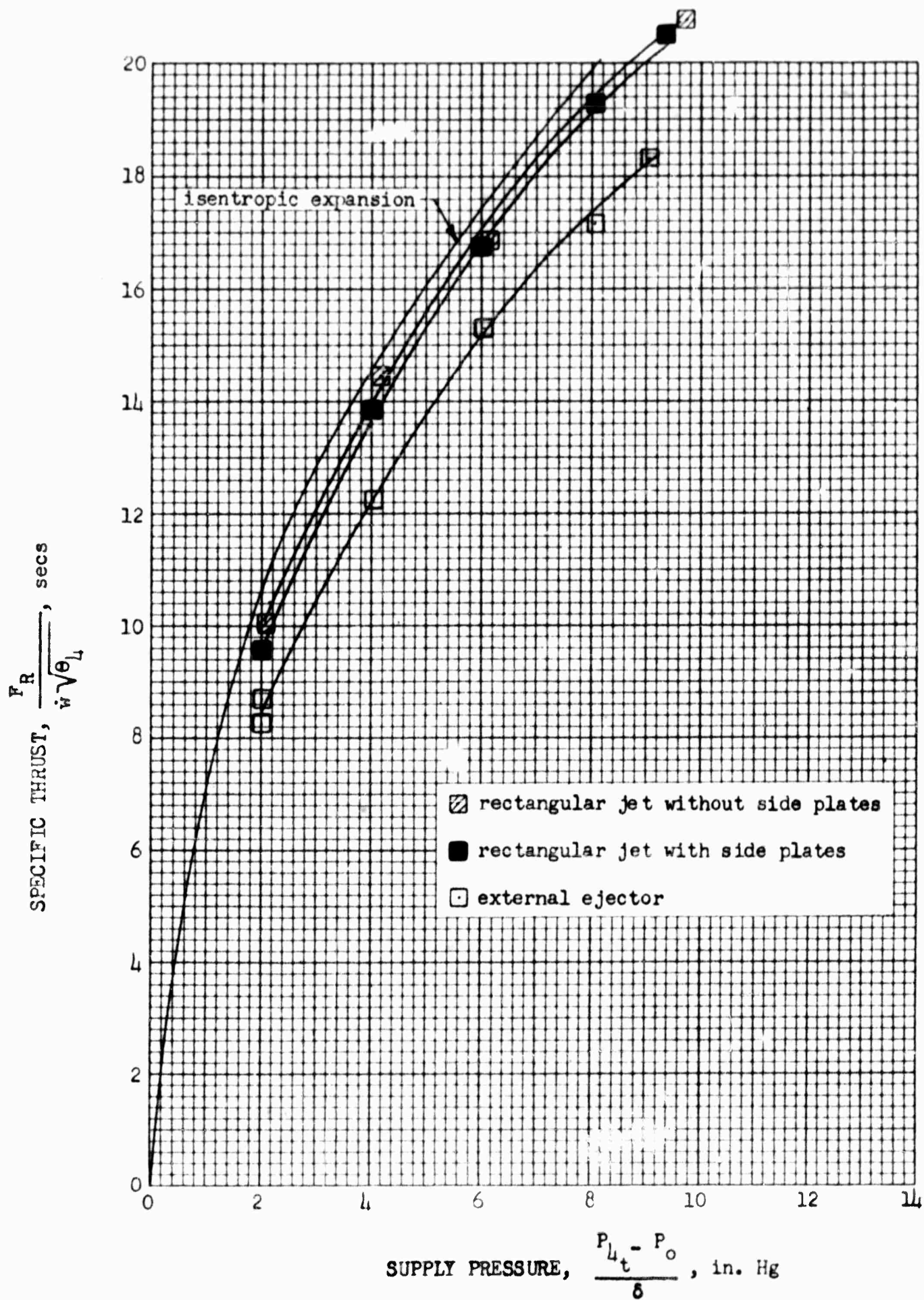
FIGURE 5:  STATIC PERFORMANCE OF TWO-DIMENSIONAL
EXTERNAL EJECTOR AT $\sigma = 4/3$
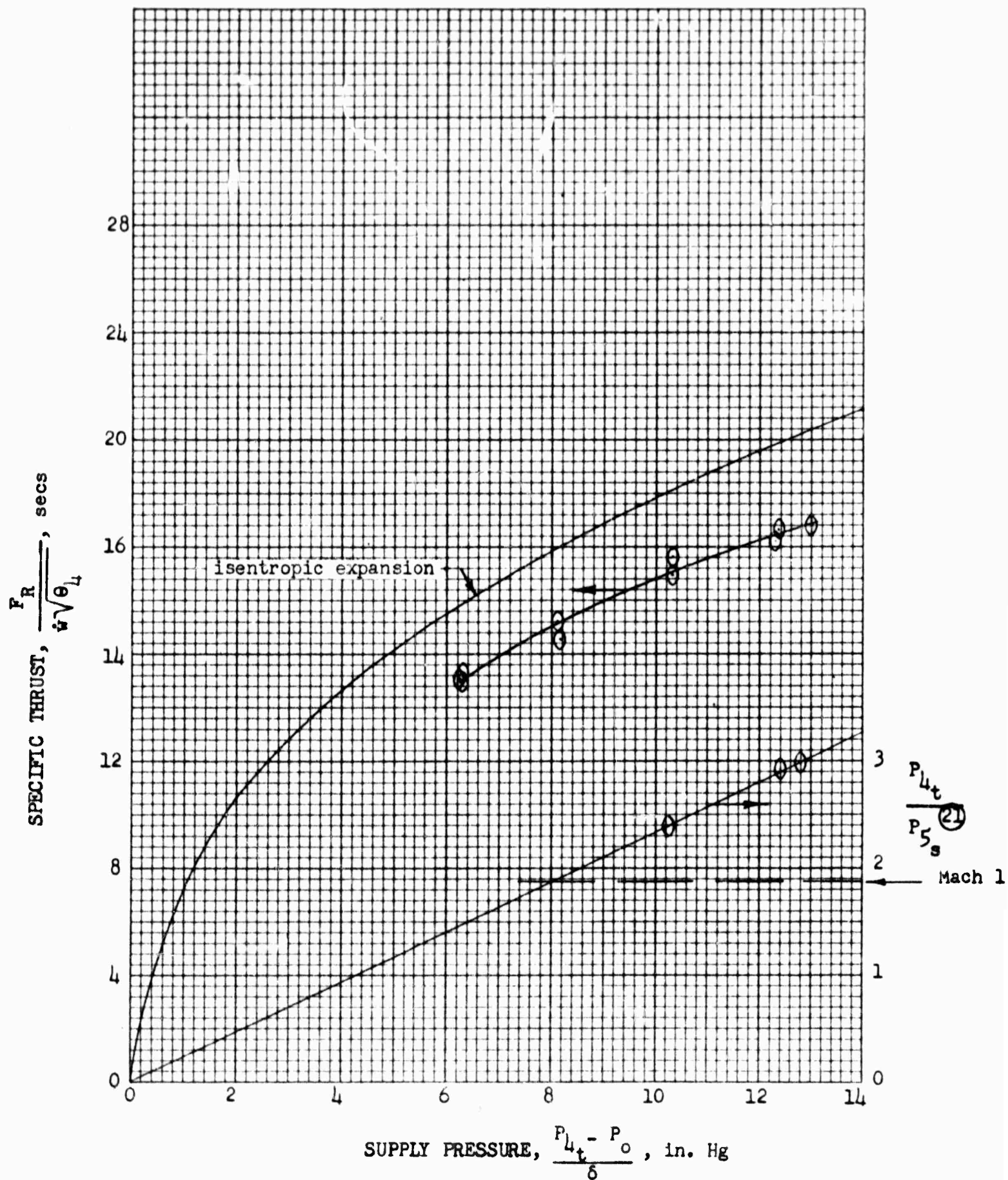
FIGURE 6:  STATIC PERFORMANCE OF TWO-DIMENSIONAL
EXTERNAL EJECTOR AT $\sigma = 1.47$

FIGURE 7:  STATIC PERFORMANCE OF TWO-DIMENSIONAL
EXTERNAL EJECTOR AT $\sigma = 2$

FIGURE 8: SURFACE STATIC PRESSURE DISTRIBUTION FOR TWO-DIMENSIONAL CONFIGURATION AT σ = 2/3
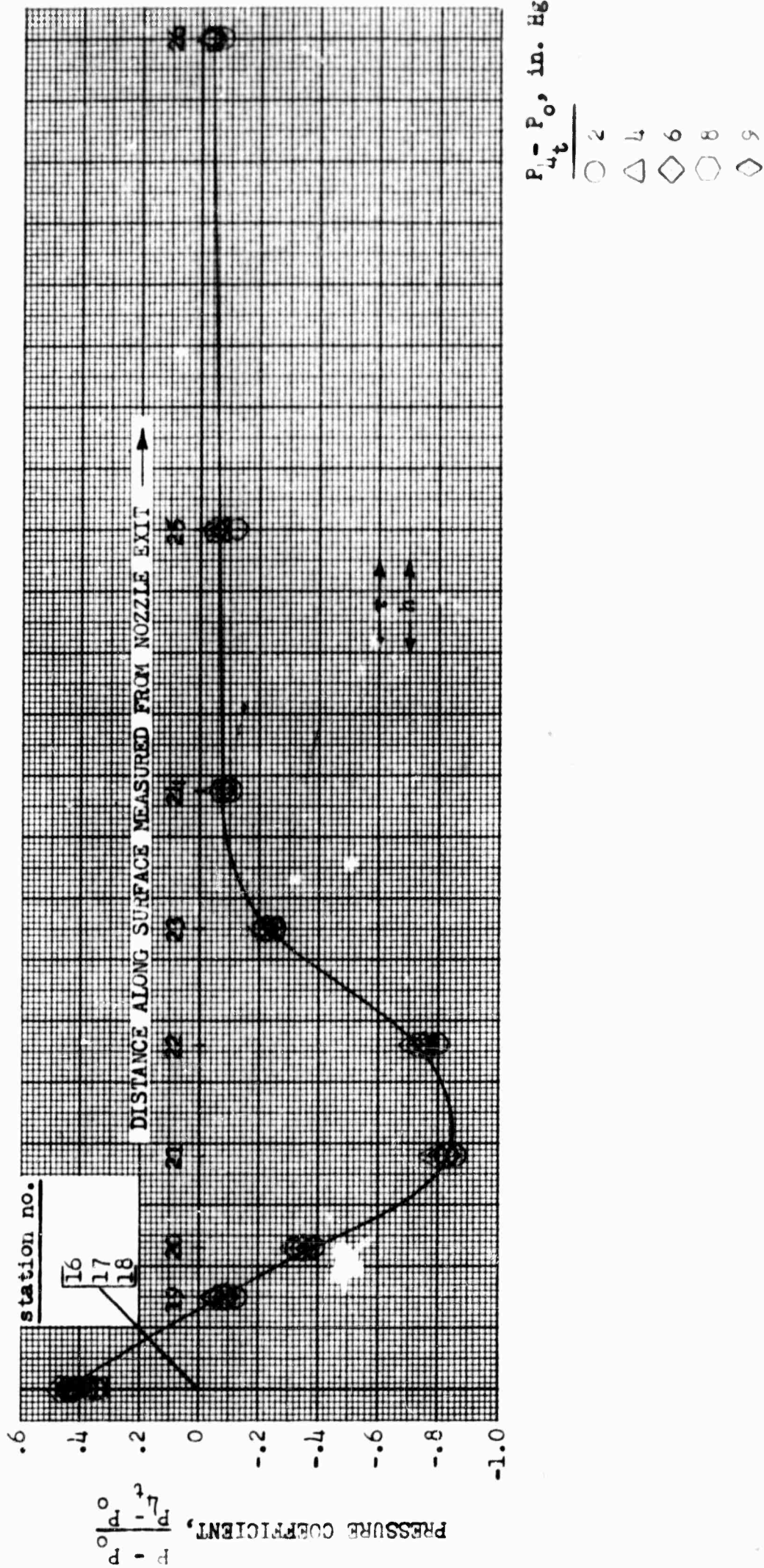
FIGURE 9:  SURFACE STATIC PRESSURE DISTRIBUTION FOR TWO-DIMENSIONAL
CONFIGURATION AT σ = 1
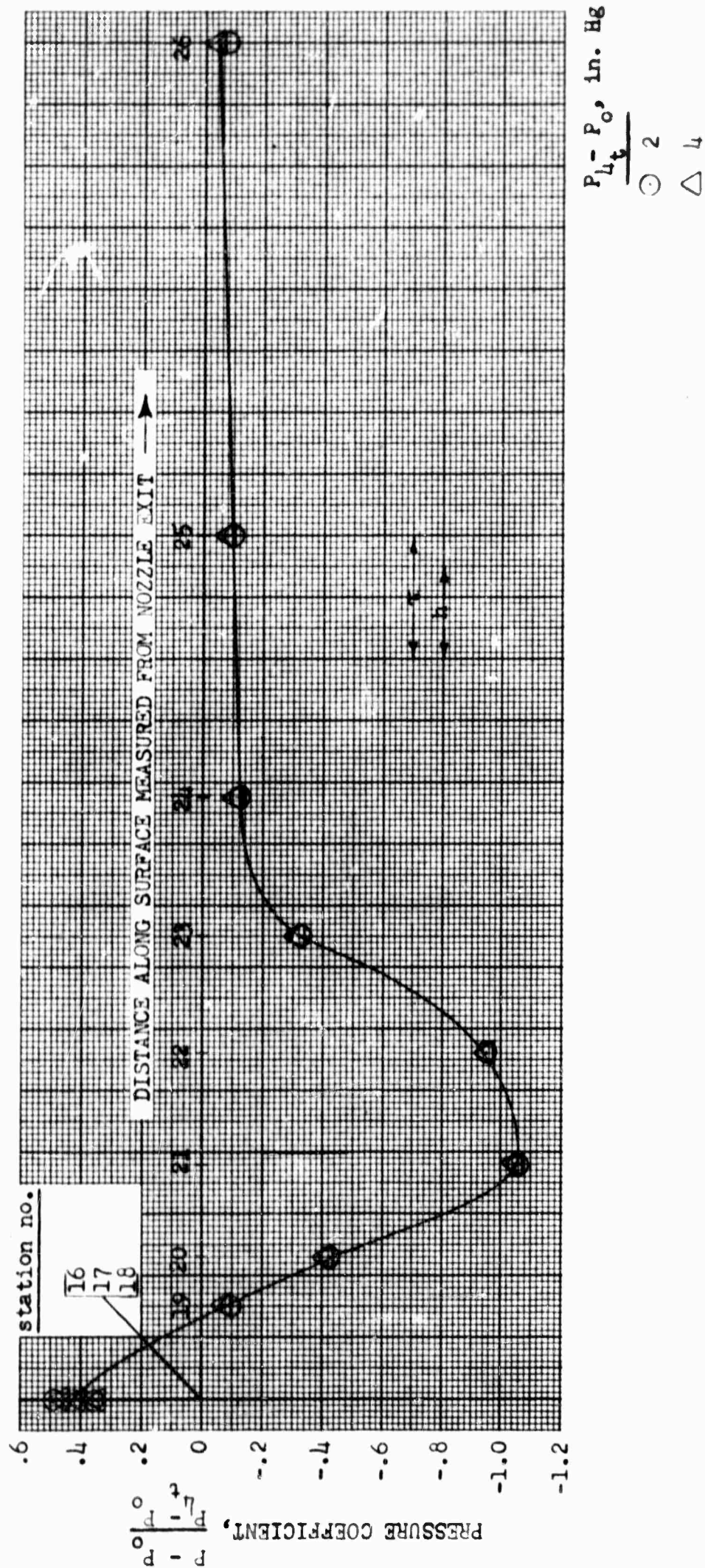
FIGURE 10: SURFACE STATIC PRESSURE DISTRIBUTION FOR TWO-DIMENSIONAL CONFIGURATION AT σ = 4/3
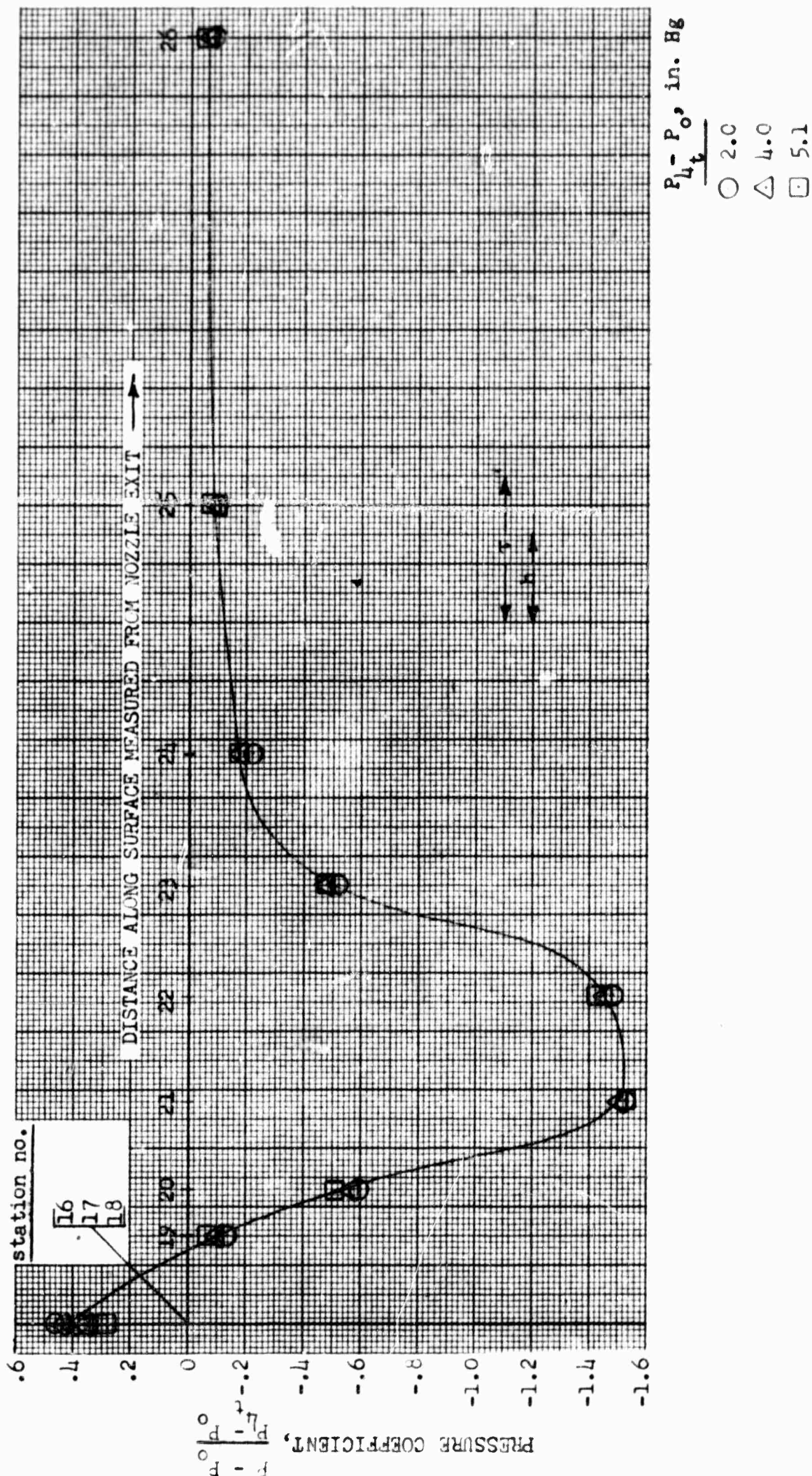
FIGURE 11: SURFACE STATIC PRESSURE DISTRIBUTION FOR TWO-DIMENSIONAL CONFIGURATION AT $\sigma = 2$
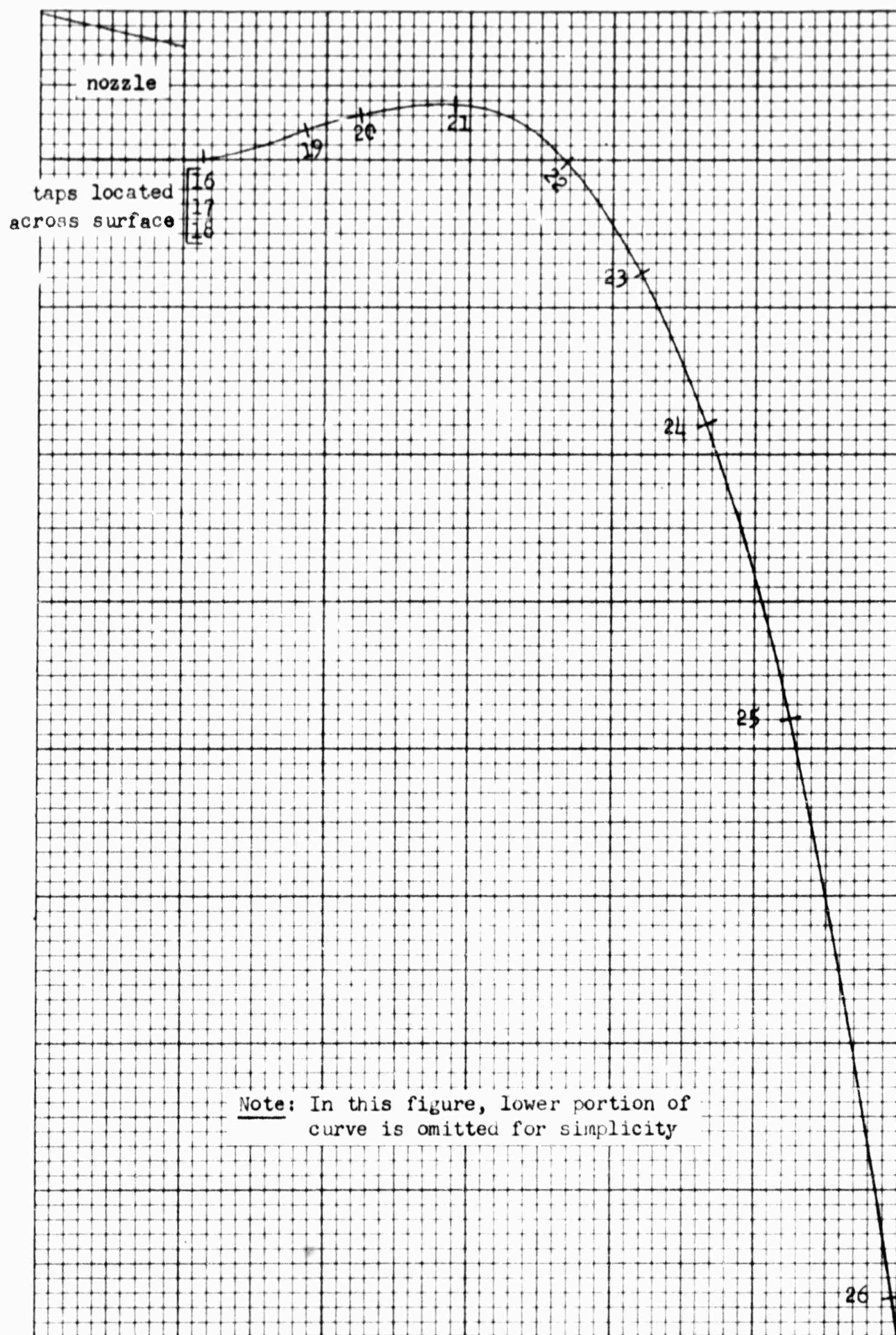
FIGURE 12: LOCATION OF PRESSURE TAPS; CROSS-SECTION THROUGH
CENTER OF TWO-DIMENSIONAL CONFIGURATION
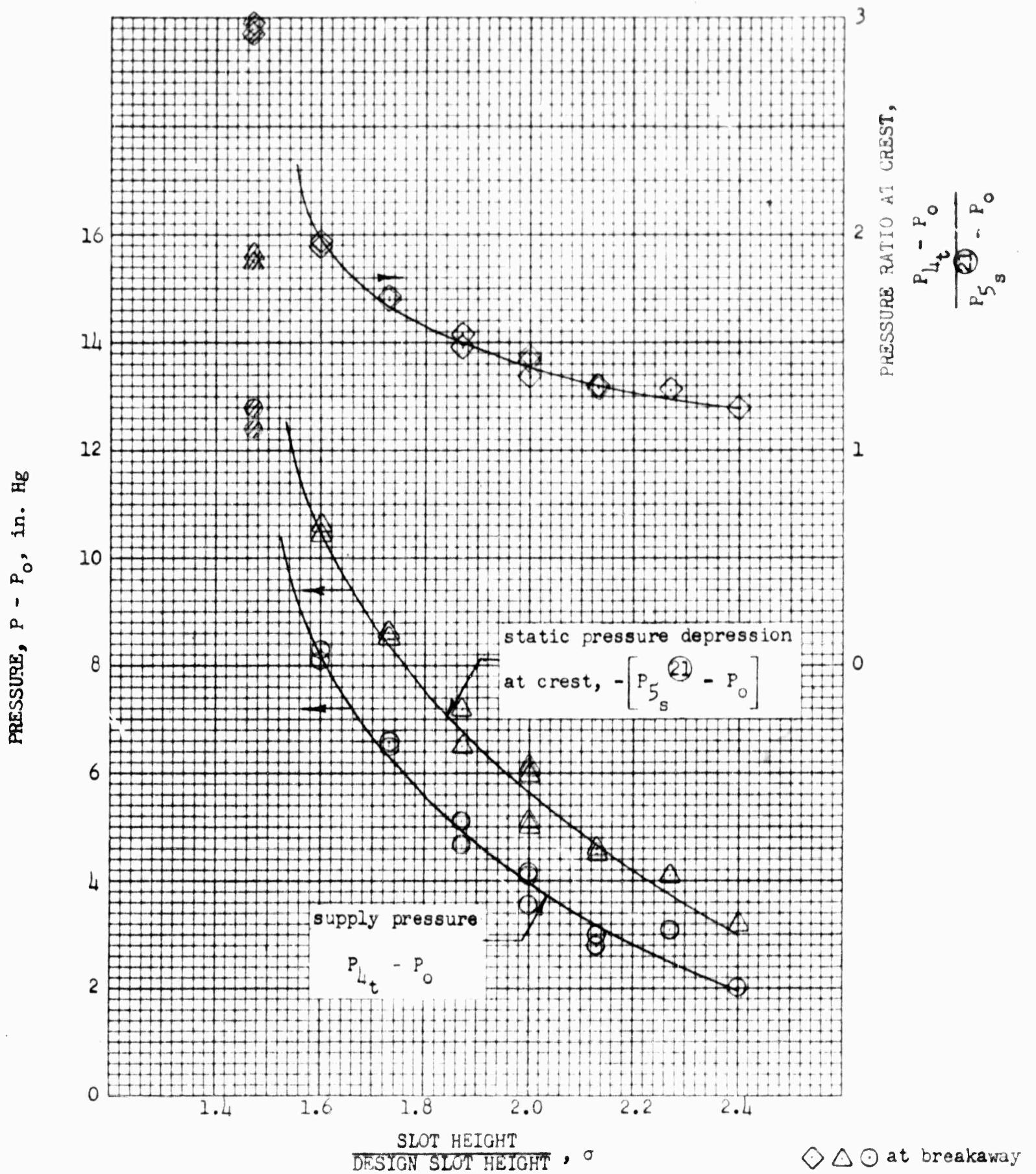
FIGURE 13: SUPPLY PRESSURE, MAXIMUM DEPRESSION AND
MAXIMUM PRESSURE RATIO AT BREAKAWAY;
TWO-DIMENSIONAL CONFIGURATION

Immediately prior
to separation
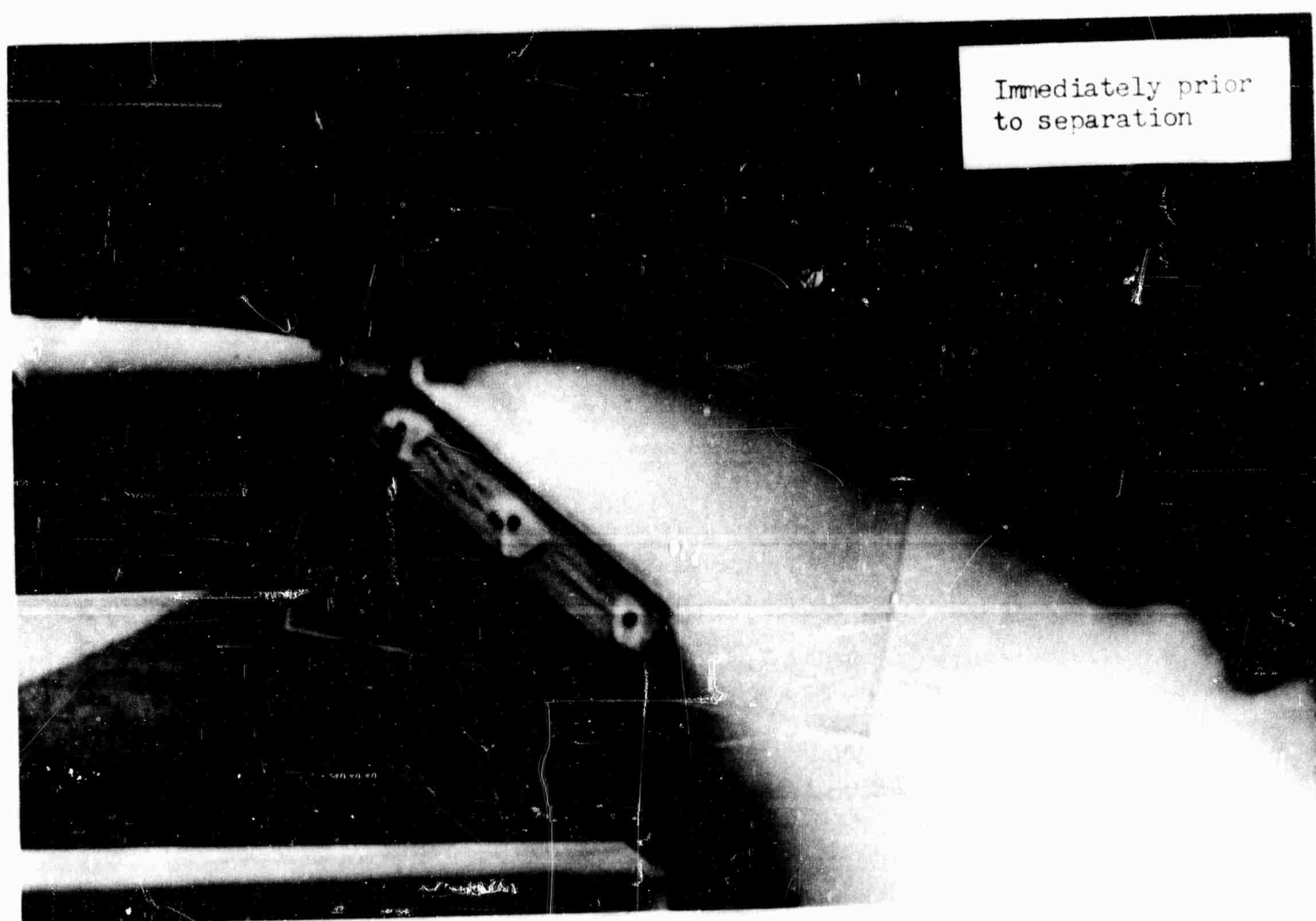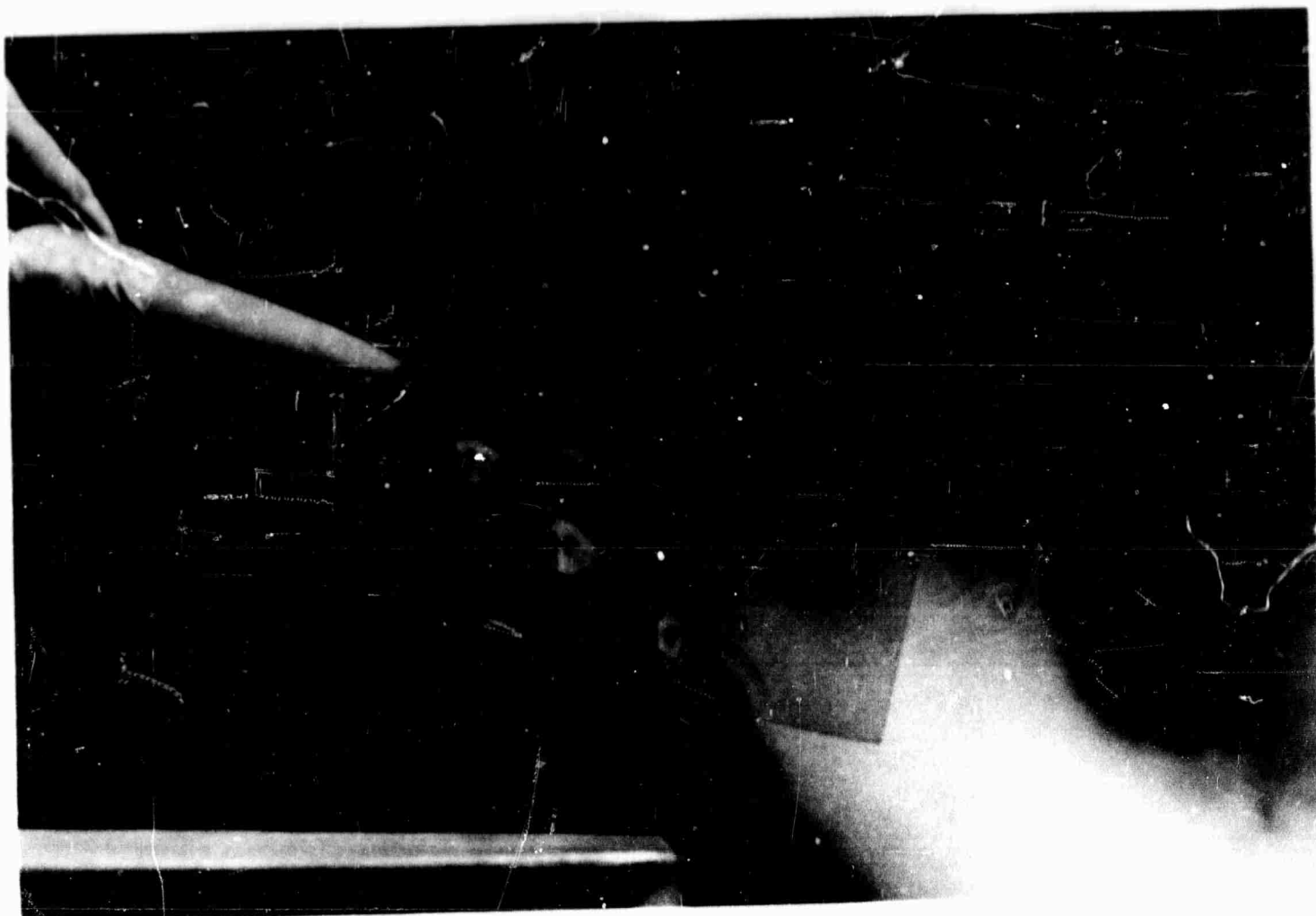
FIGURE 14:  RECTANGULAR NOZZLE - FLAT PLATE DEFLECTION SURFACE
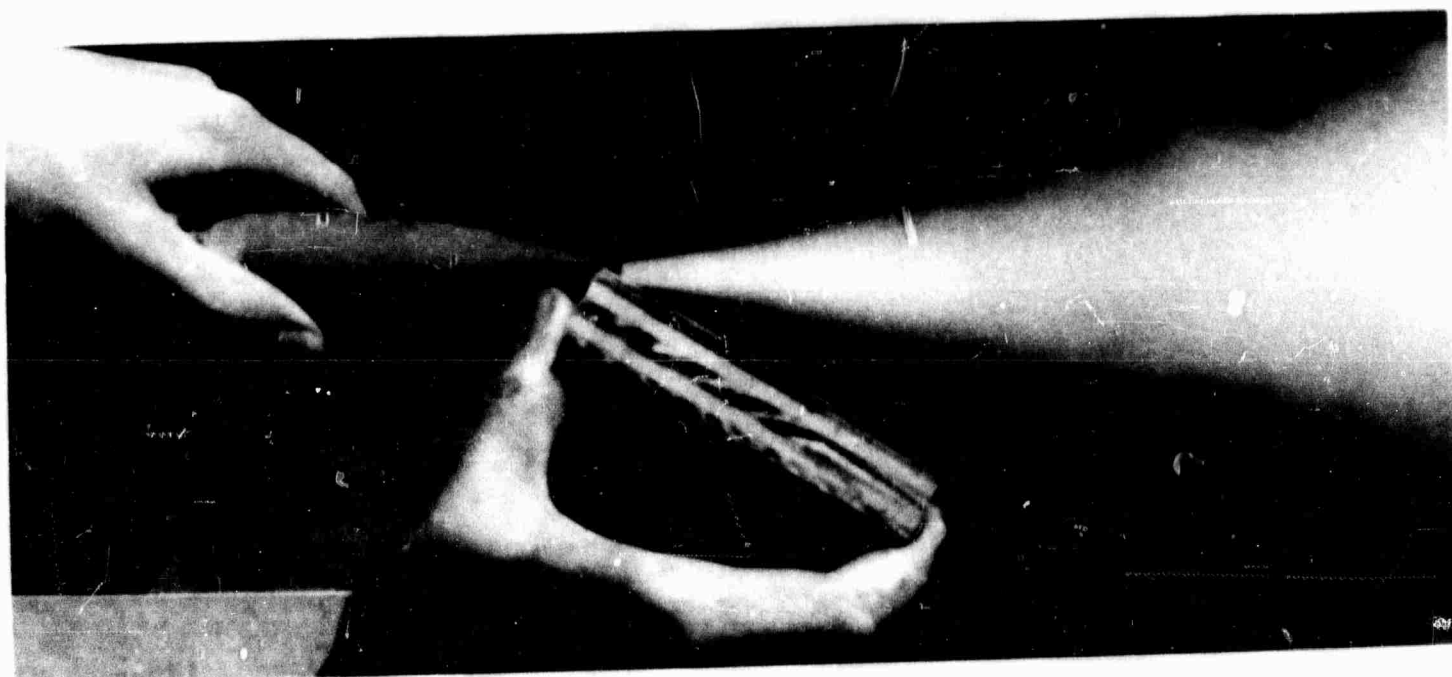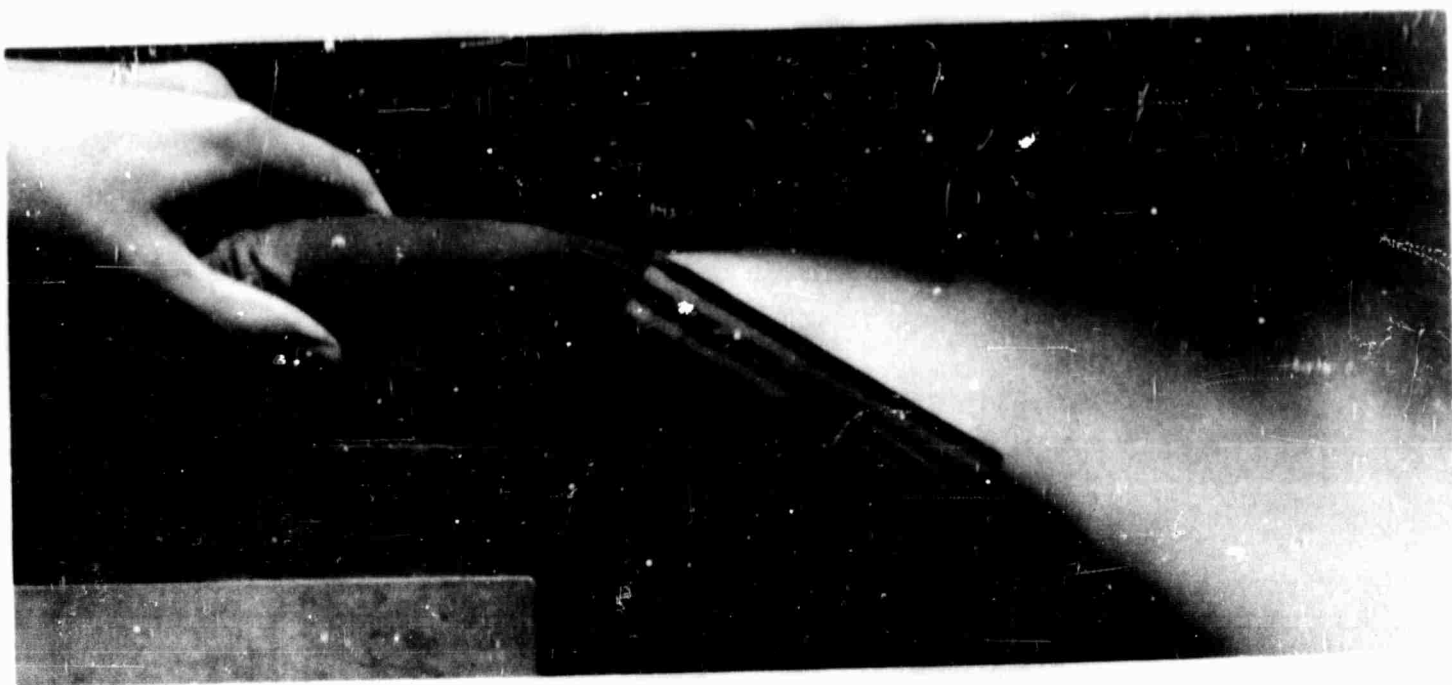
FIGURE 15: RECTANGULAR NOZZLE - FLAT PLATE DEFLECTION SURFACE
WITHOUT SIDE PLATES
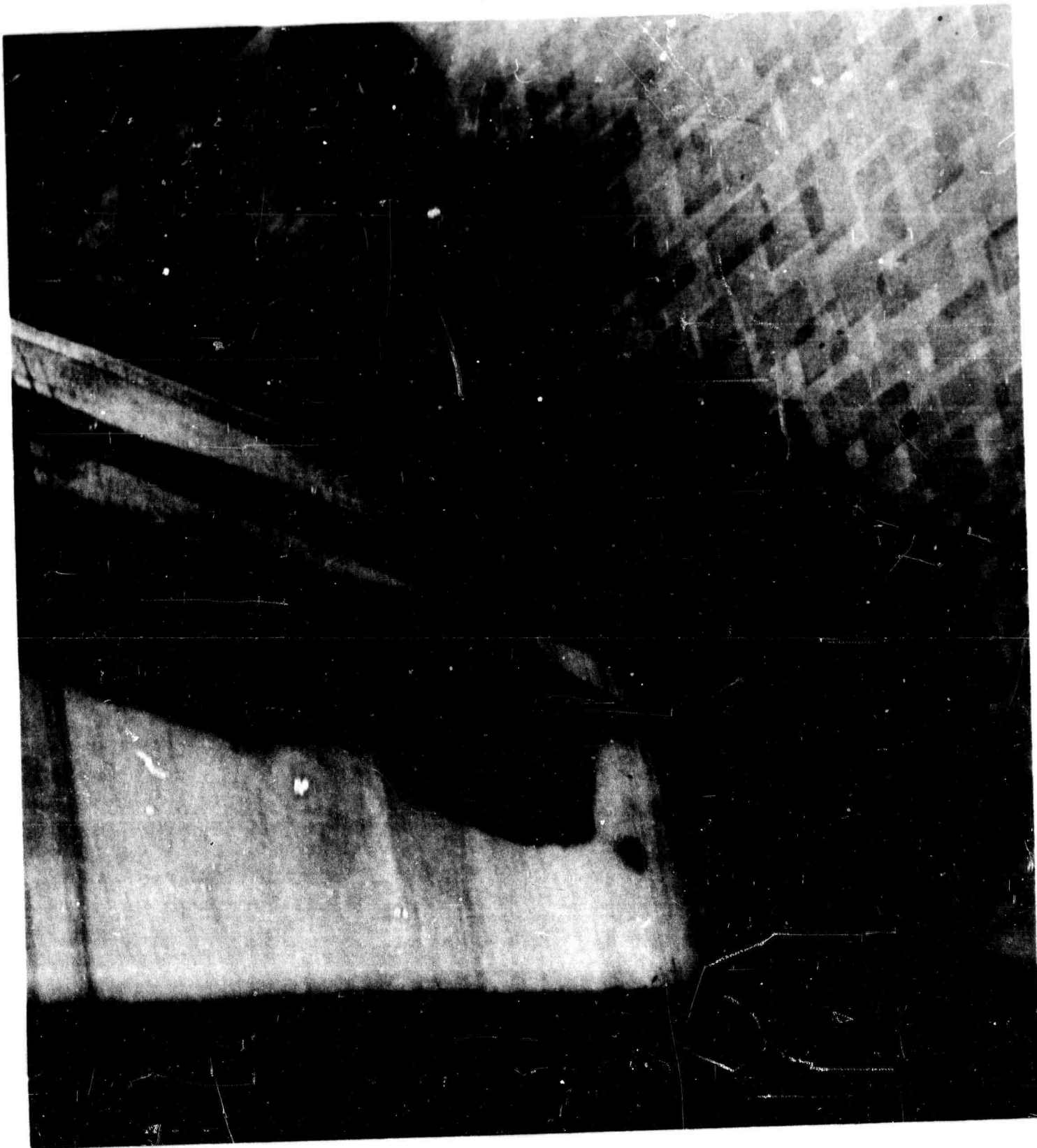
FIGURE 16: SMOKE TRACE OF SECONDARY FLOW AT CREST
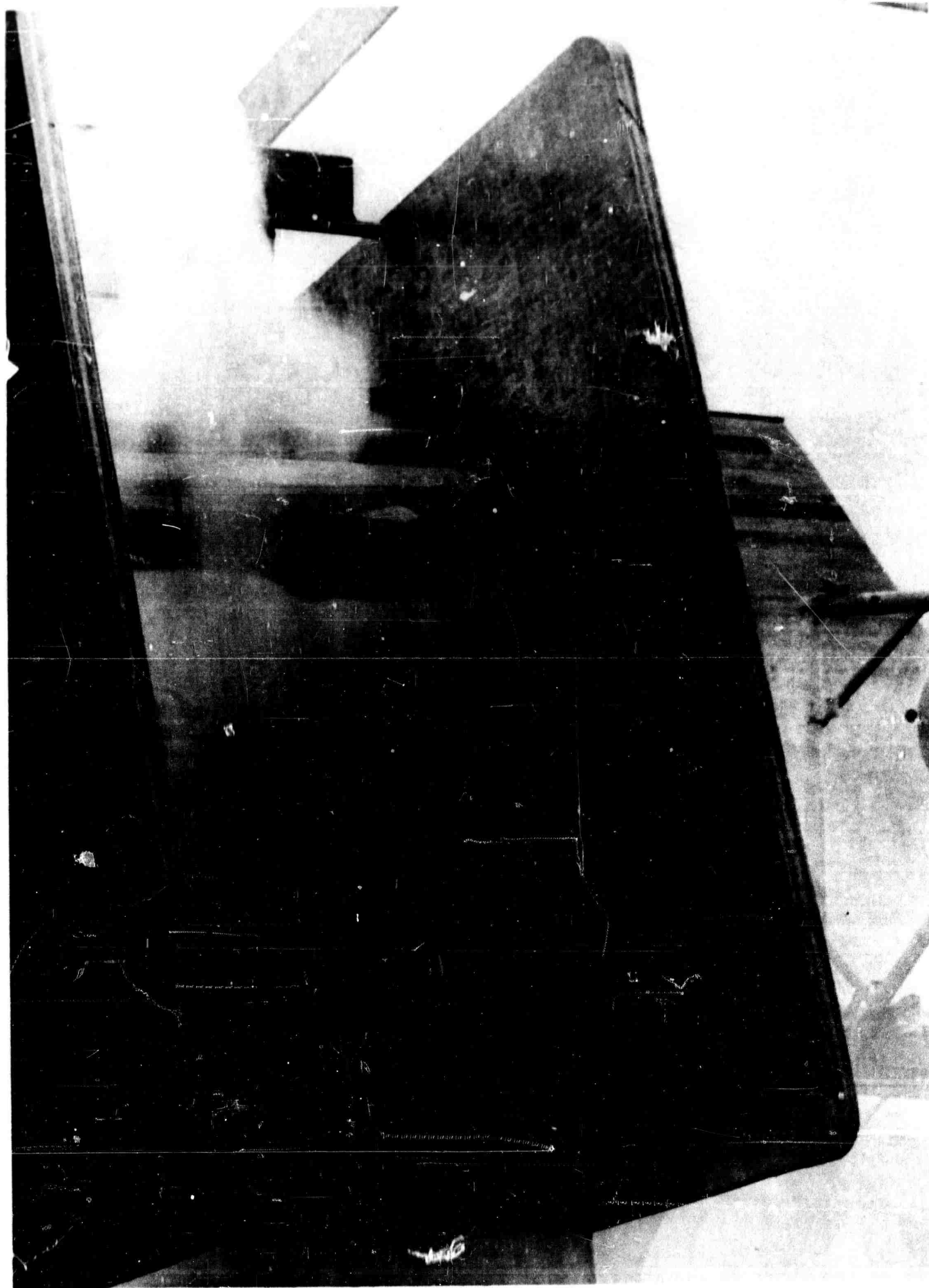
FIGURE 17: SMOKE TRACE OF SECONDARY FLOW
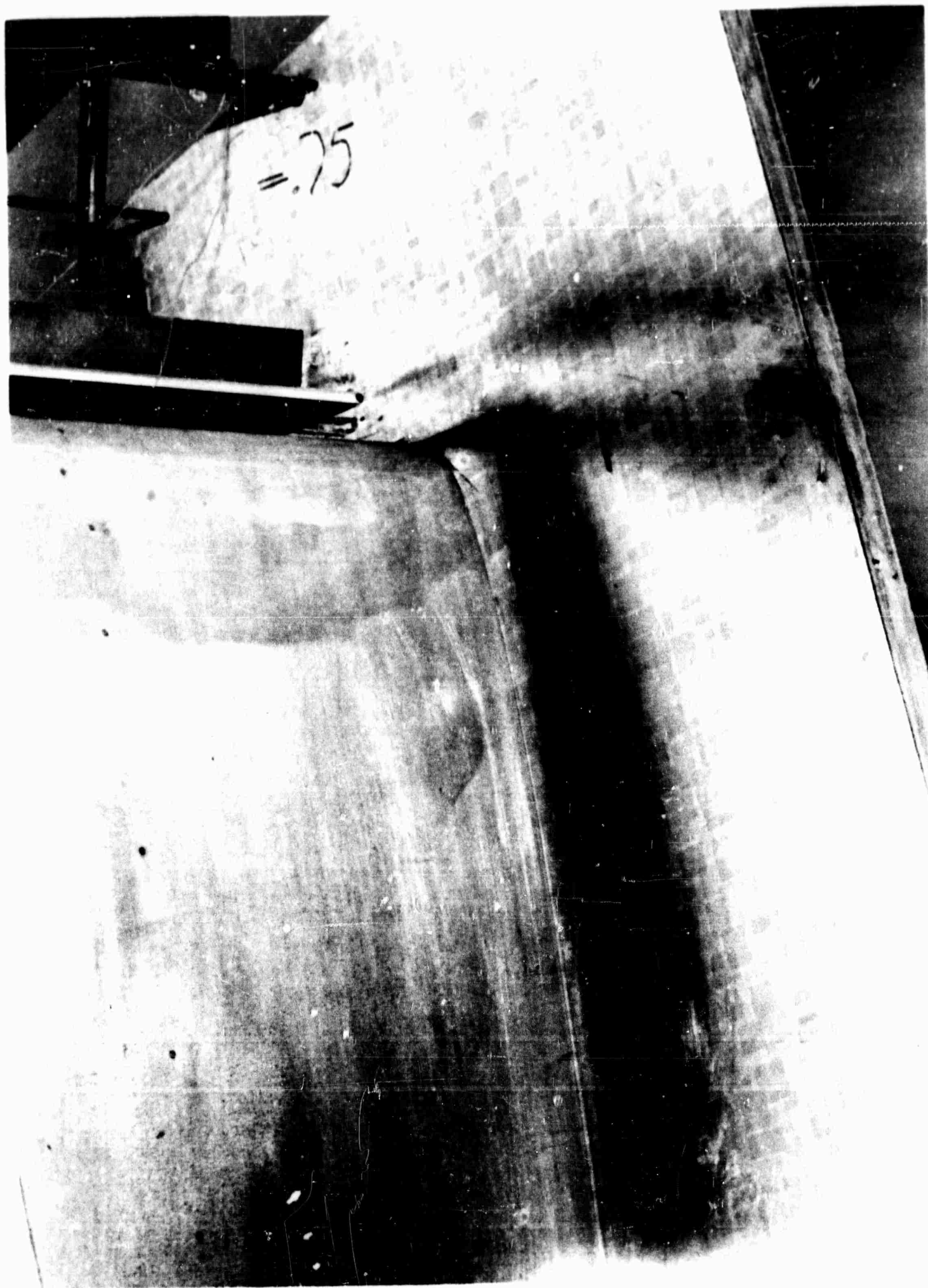
FIGURE 18: SMOKE TRACE OF SECONDARY FLOW IN BOTH THE ATTACHED
AND SEPARATED CONDITIONS

flat sheet temporarily
added to simulate
internal flow ejector

side plate

nozzle
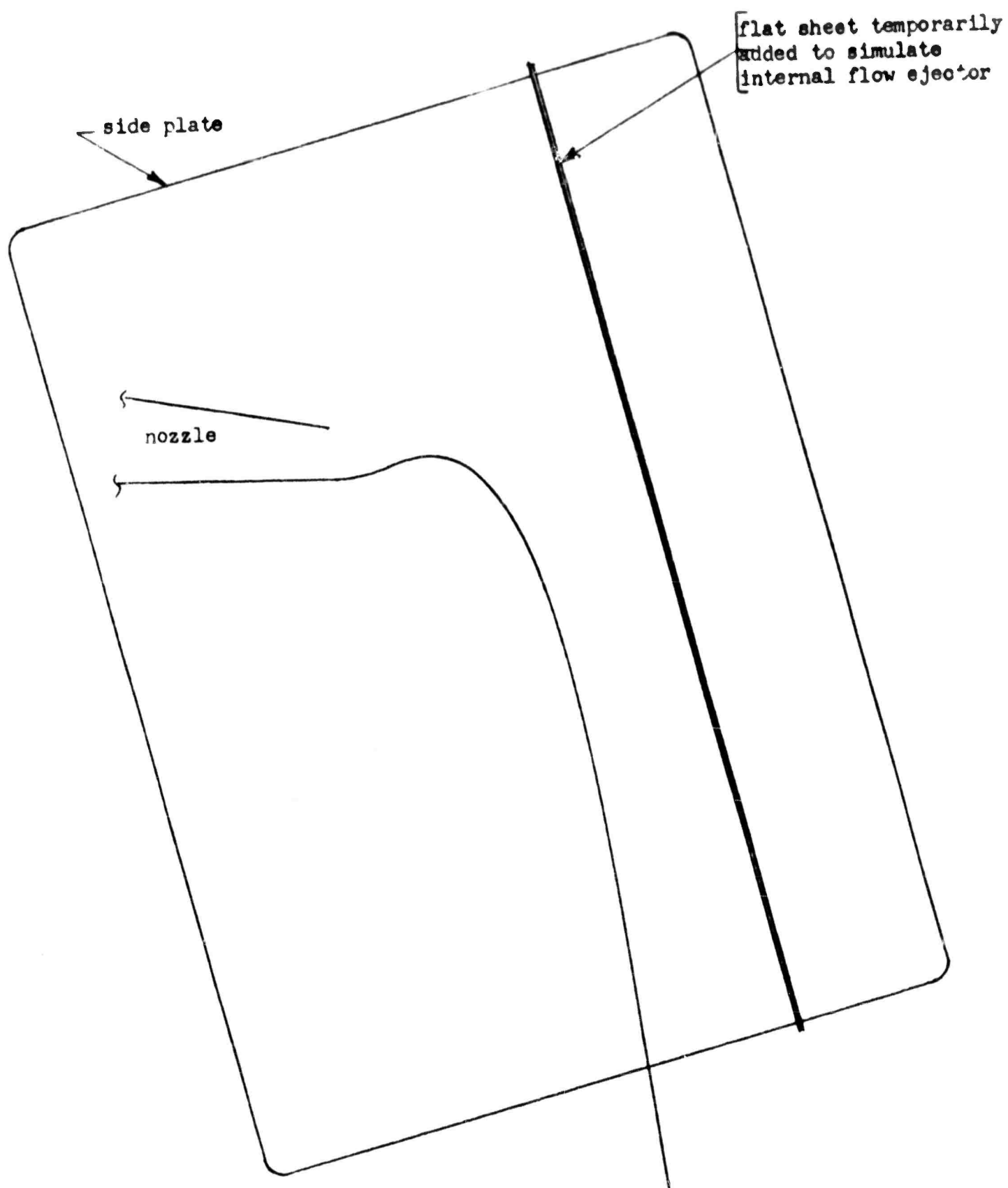
FIGURE 19: CROSS SECTION OF TWO-DIMENSIONAL EXTERNAL FLOW EJECTOR
MODIFIED TO SIMULATE INTERNAL FLOW EJECTOR
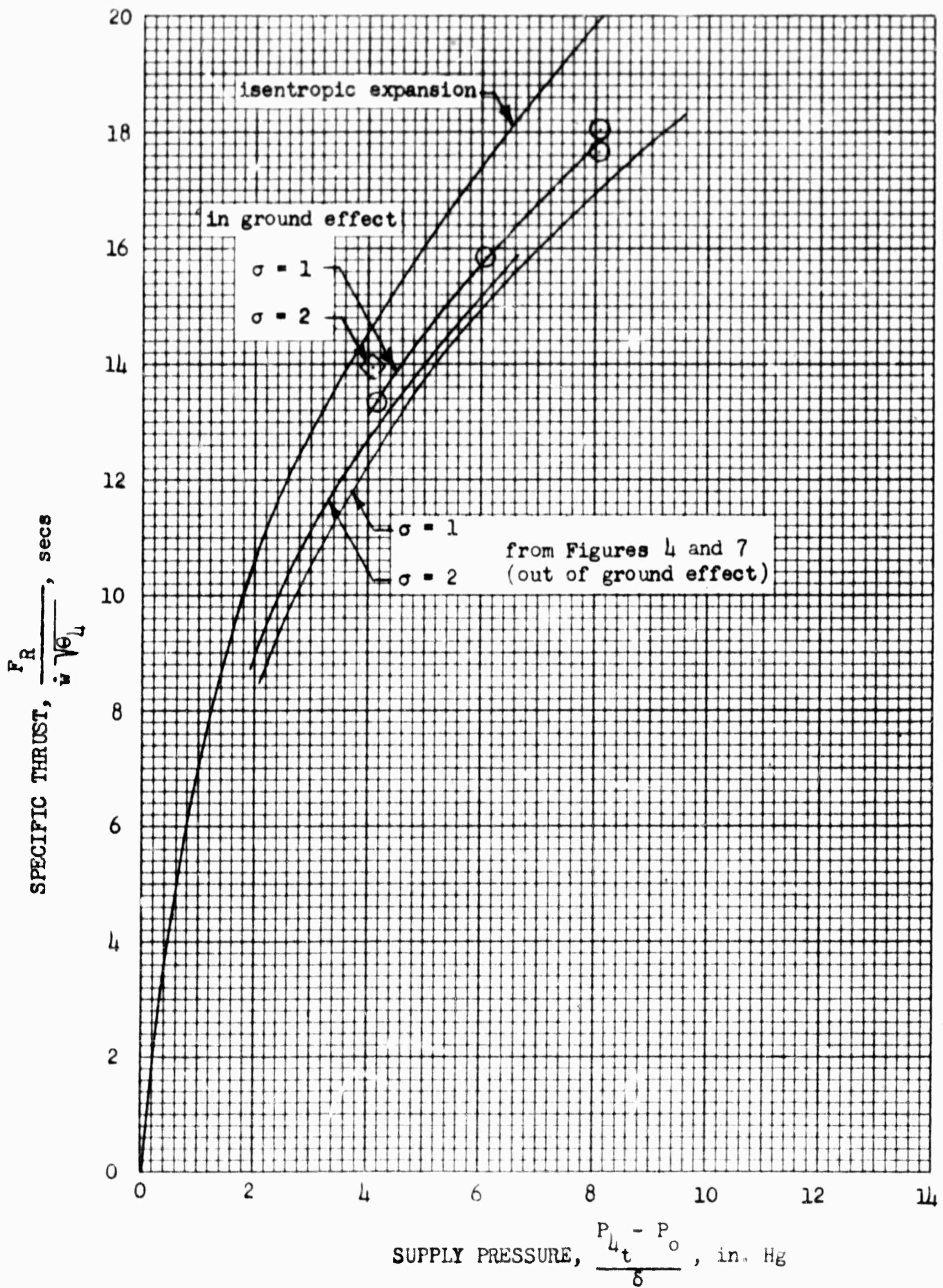
FIGURE 20: GROUND EFFECT ON STATIC PERFORMANCE OF
TWO-DIMENSIONAL EXTERNAL EJECTOR;
GROUND CLEARANCE = $2\tau$
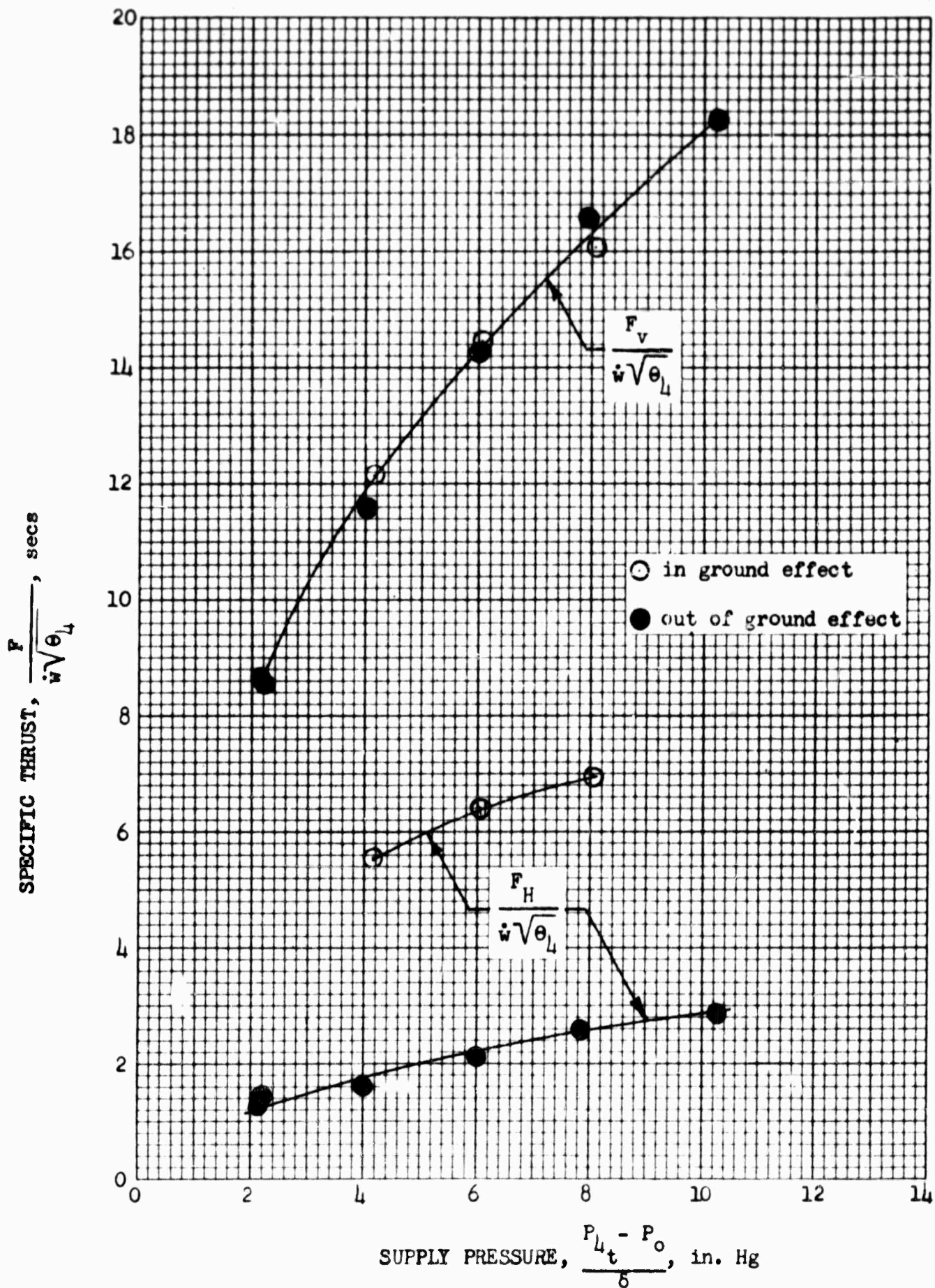
FIGURE 21: COMPARISON OF GROUND EFFECT ON VERTICAL AND HORIZONTAL REACTIONS; STATIC PERFORMANCE OF EXTERNAL EJECTOR AT $\sigma = 1$
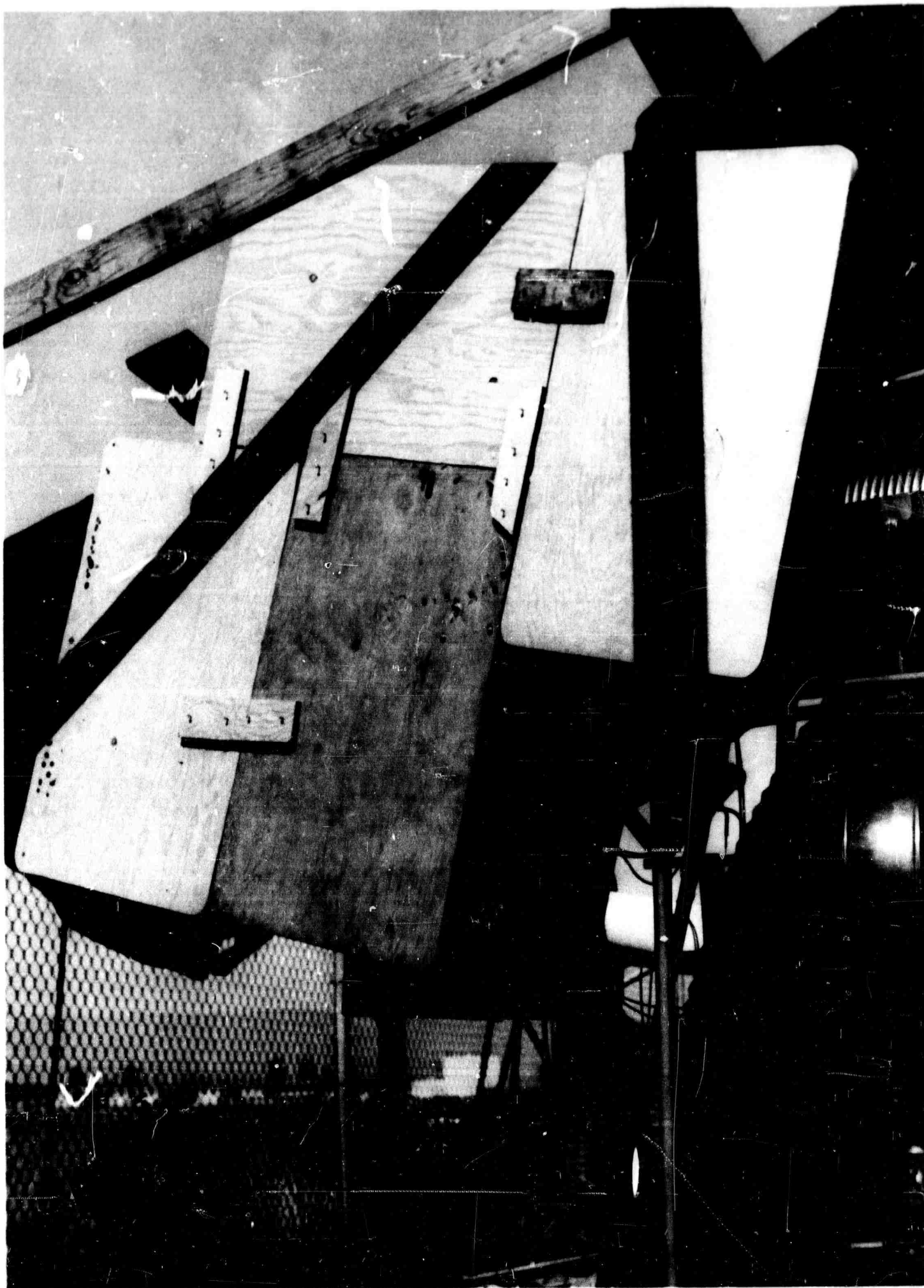
FIGURE 22: TWO-DIMENSIONAL EXTERNAL EJECTOR WITH INCREASED SIDE PLATE AREA

FIGURE 23A: THREE-DIMENSIONAL EXTERNAL EJECTOR
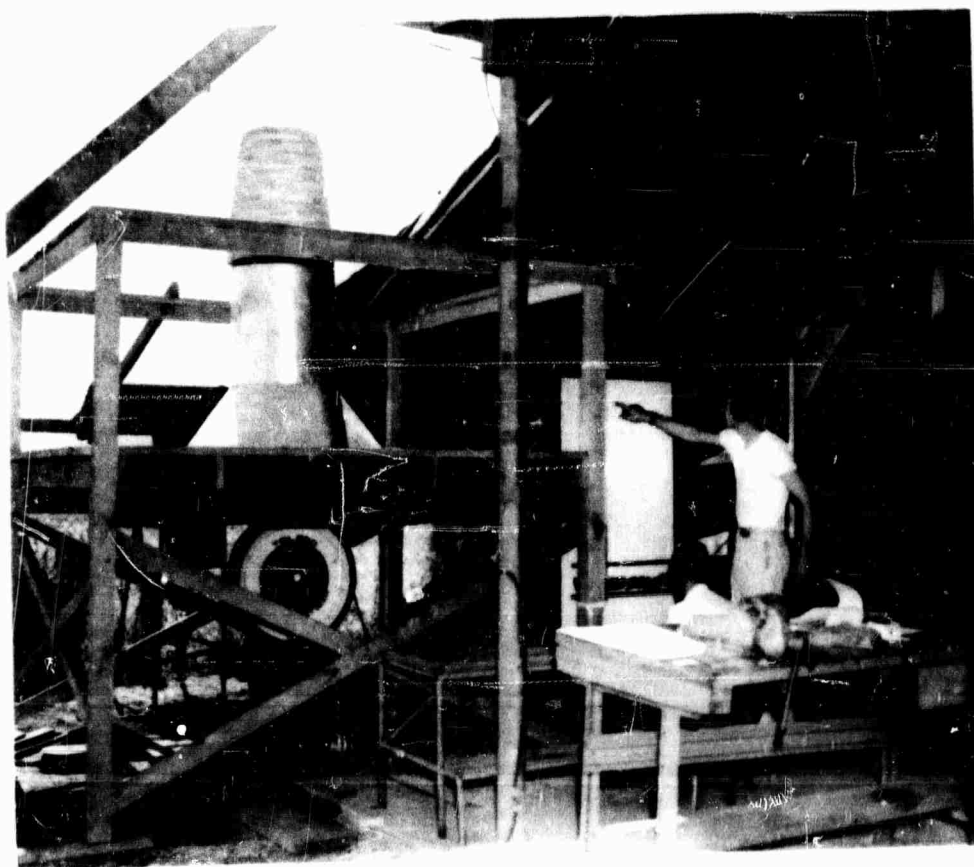


FIGURE 23B: THREE-DIMENSIONAL EXTERNAL EJECTOR ON TEST STAND

FIGURE 24: THREE-DIMENSIONAL EXTERNAL EJECTOR WITH CAP REMOVED
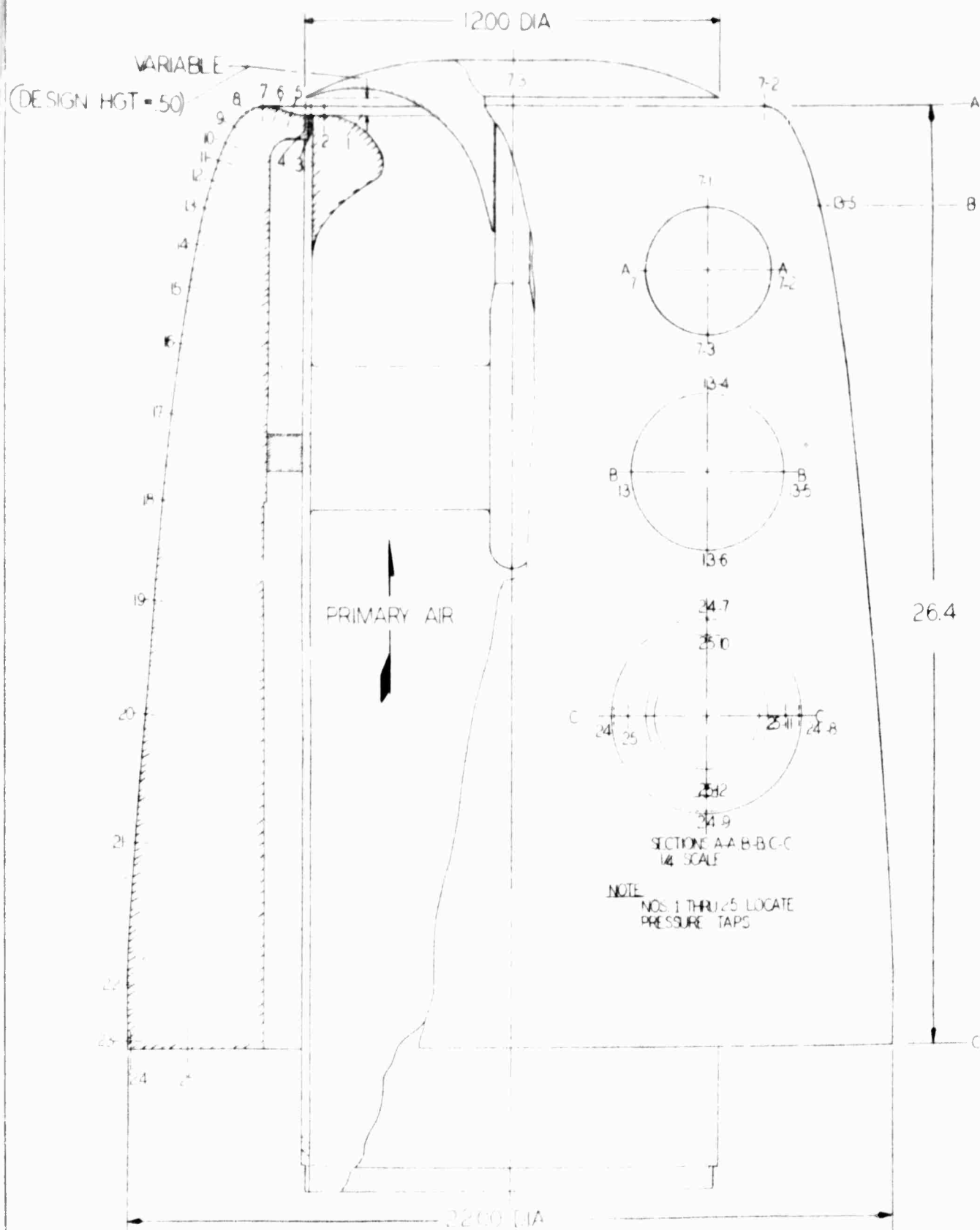
FIGURE 25:  CROSS SECTION OF THREE-DIMENSIONAL EXTERNAL EJECTOR
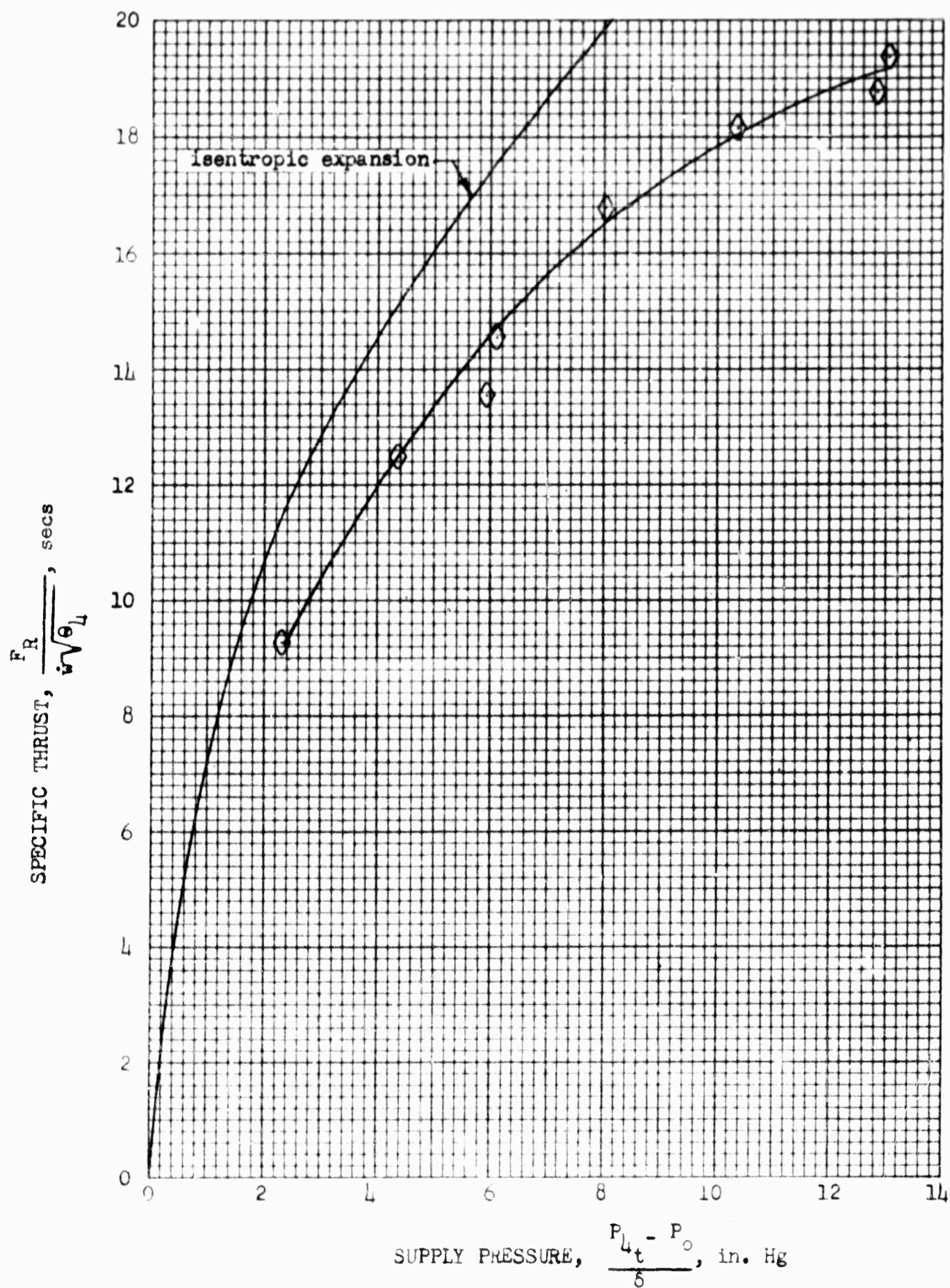
FIGURE 26: STATIC PERFORMANCE OF THREE-DIMENSIONAL
EXTERNAL EJECTOR AT σ = 3/4
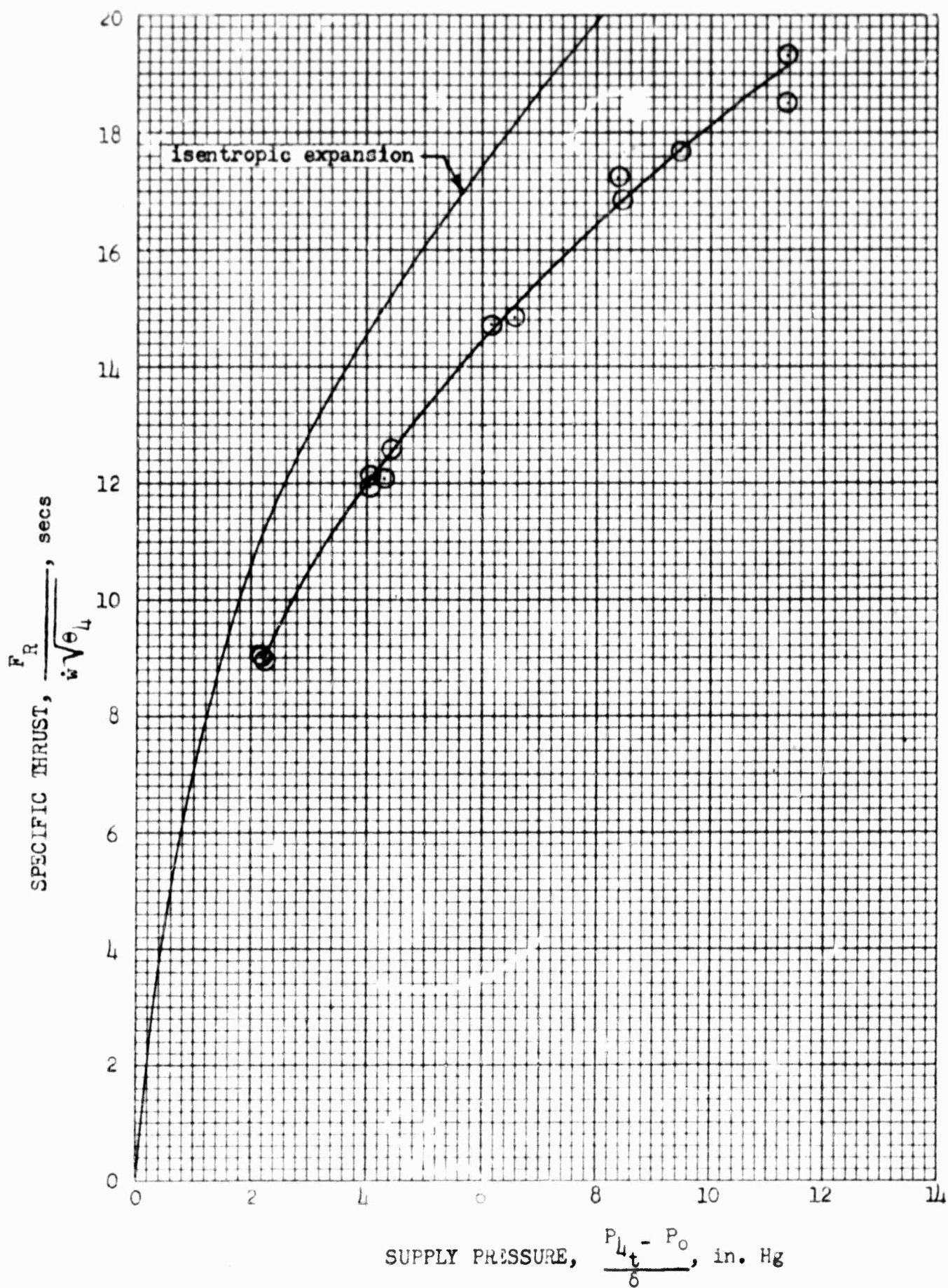
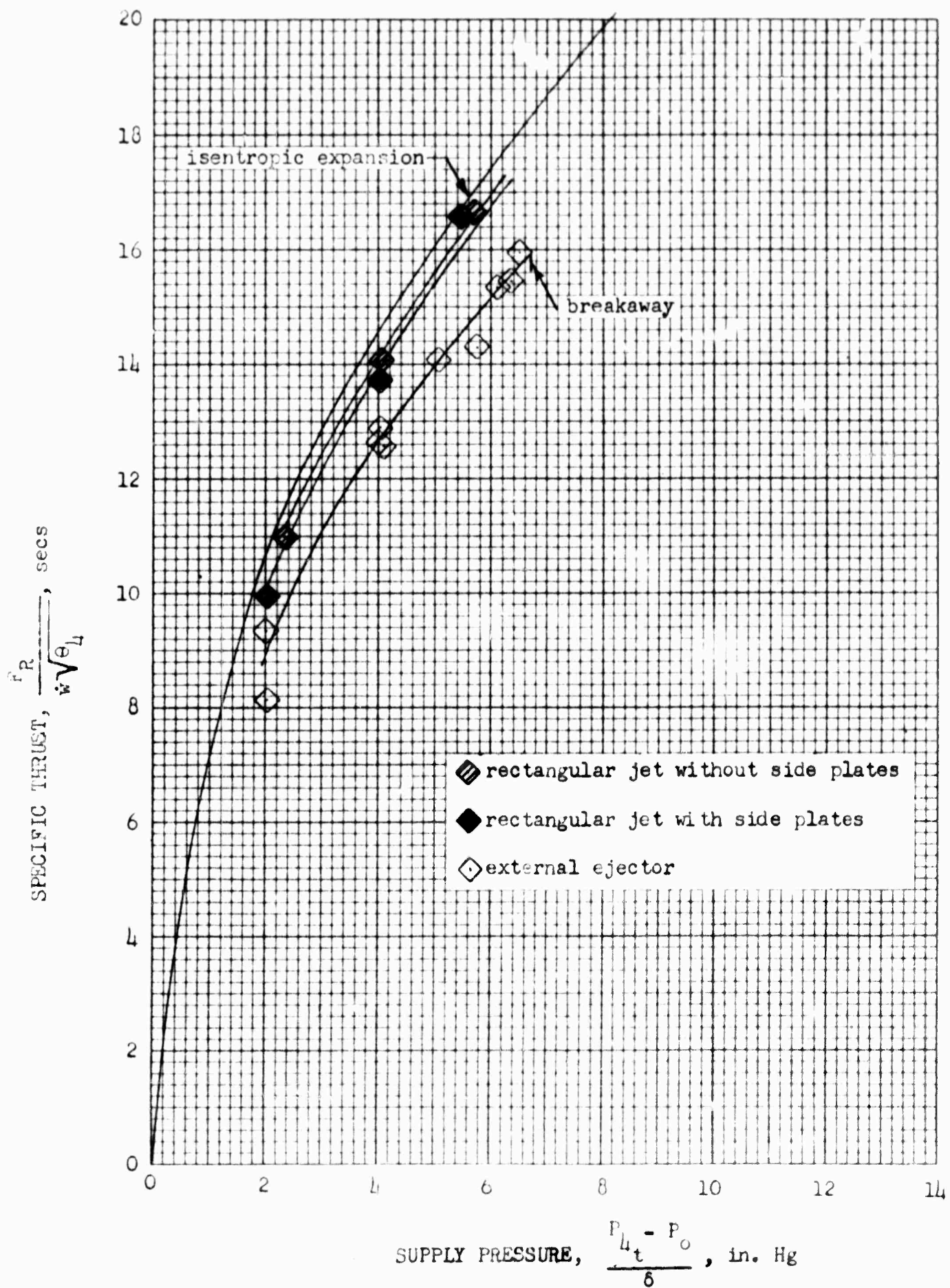FIGURE 27:  STATIC PERFORMANCE OF THREE-DIMENSIONAL
EXTERNAL EJECTOR AT σ = 1.0
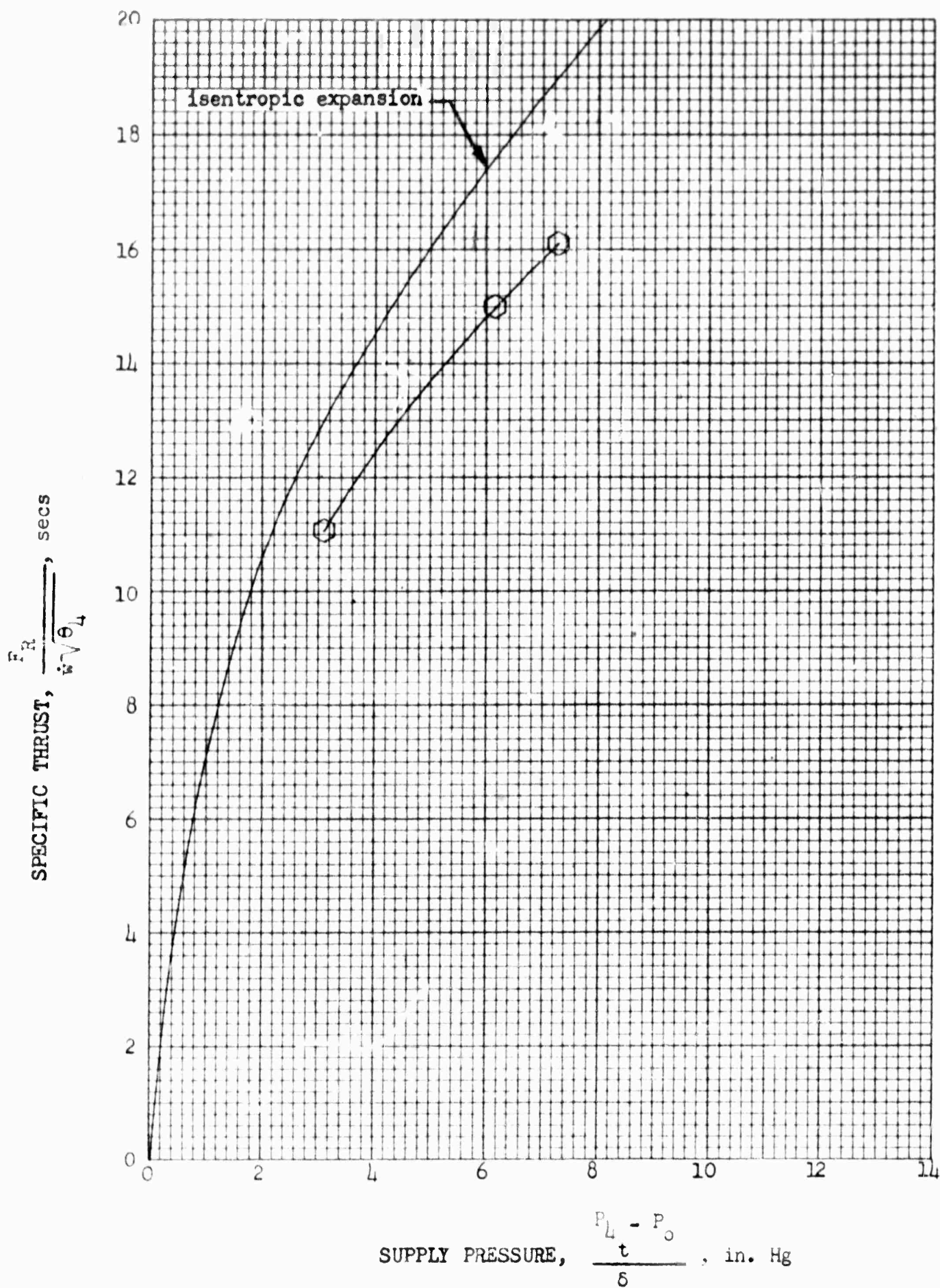
FIGURE 28: STATIC PERFORMANCE OF THREE-DIMENSIONAL
EXTERNAL EJECTOR AT $\sigma = 1.5$
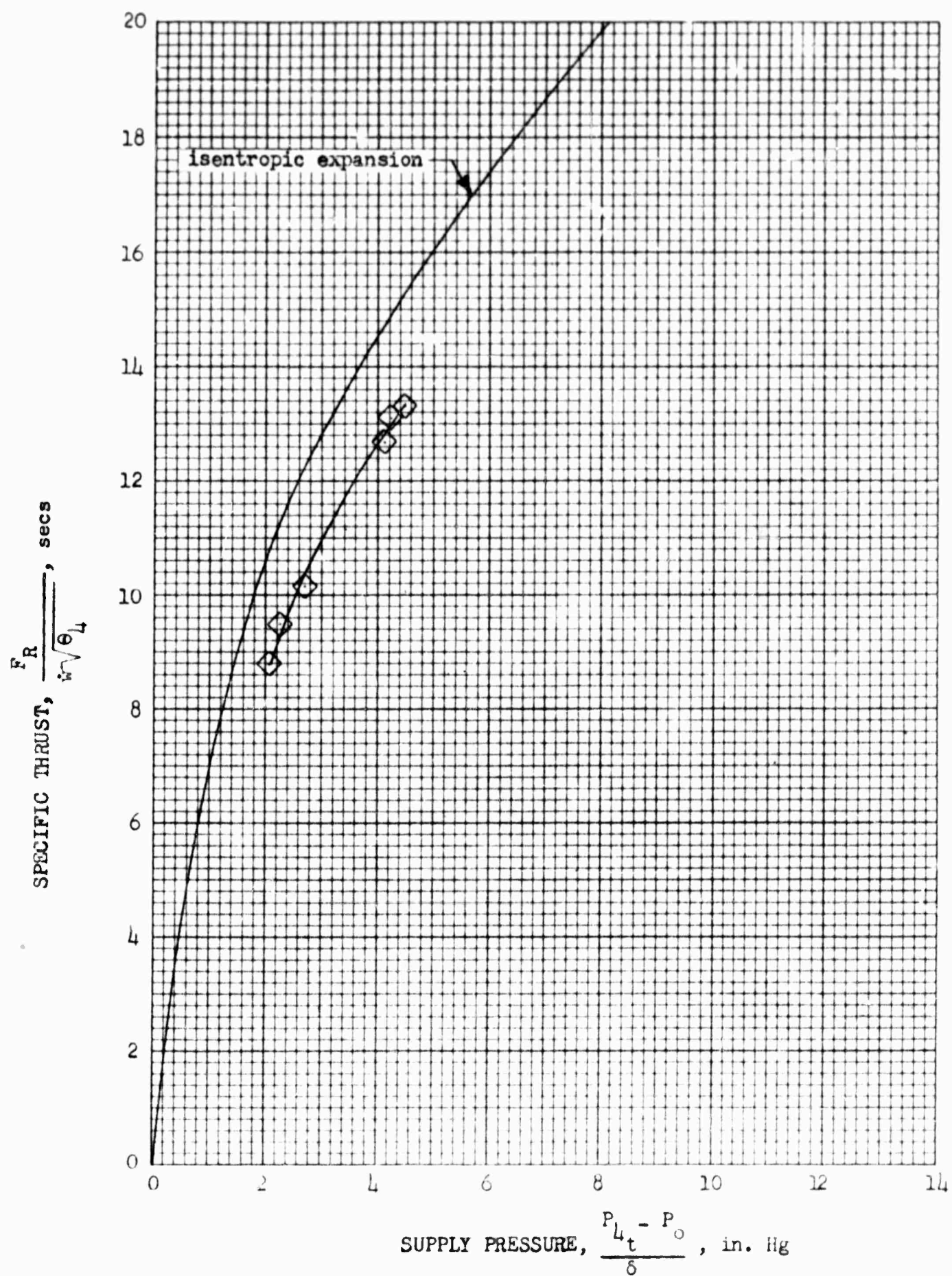
FIGURE 29: STATIC PERFORMANCE OF THREE-DIMENSIONAL
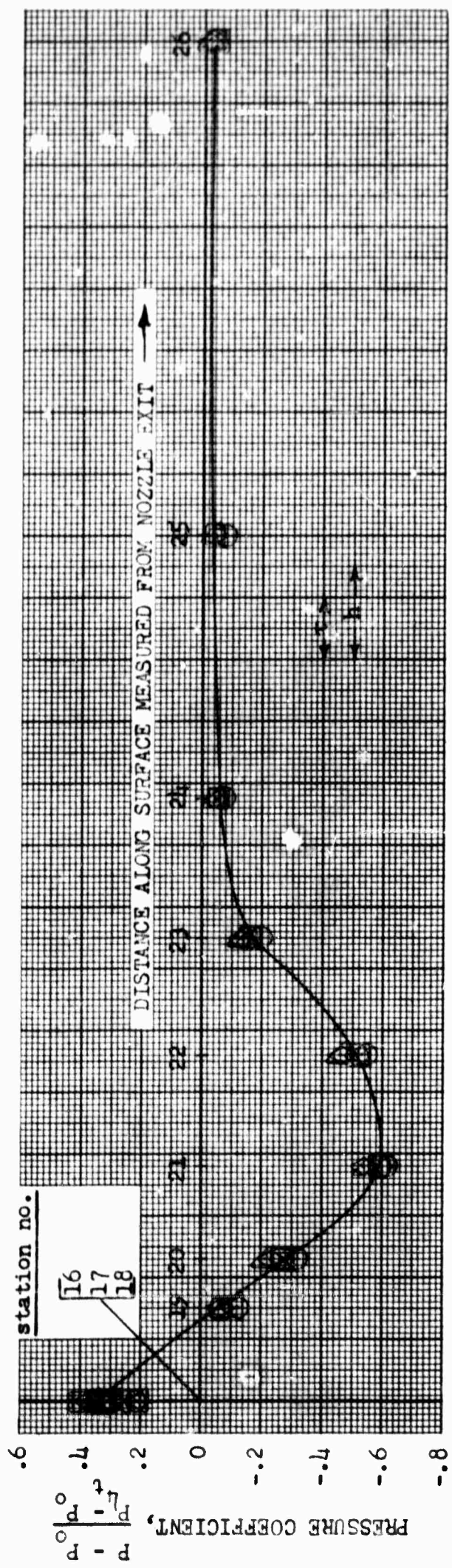EXTERNAL EJECTOR AT $\sigma = 2$
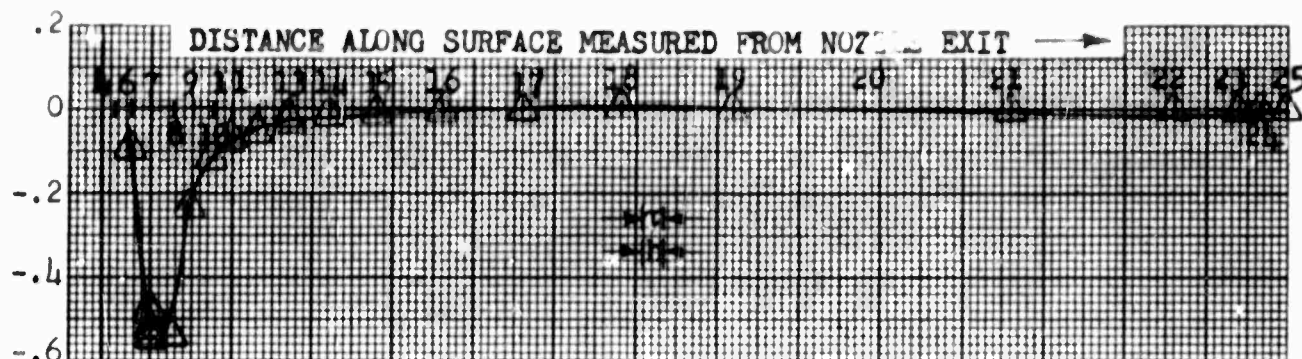
FIGURE 30:  SURFACE STATIC PRESSURE DISTRIBUTION FOR THREE-DIMENSIONAL
CONFIGURATION AT $\sigma = 1$, $P_{4_t} - P_o = 4.05$ in. Hg
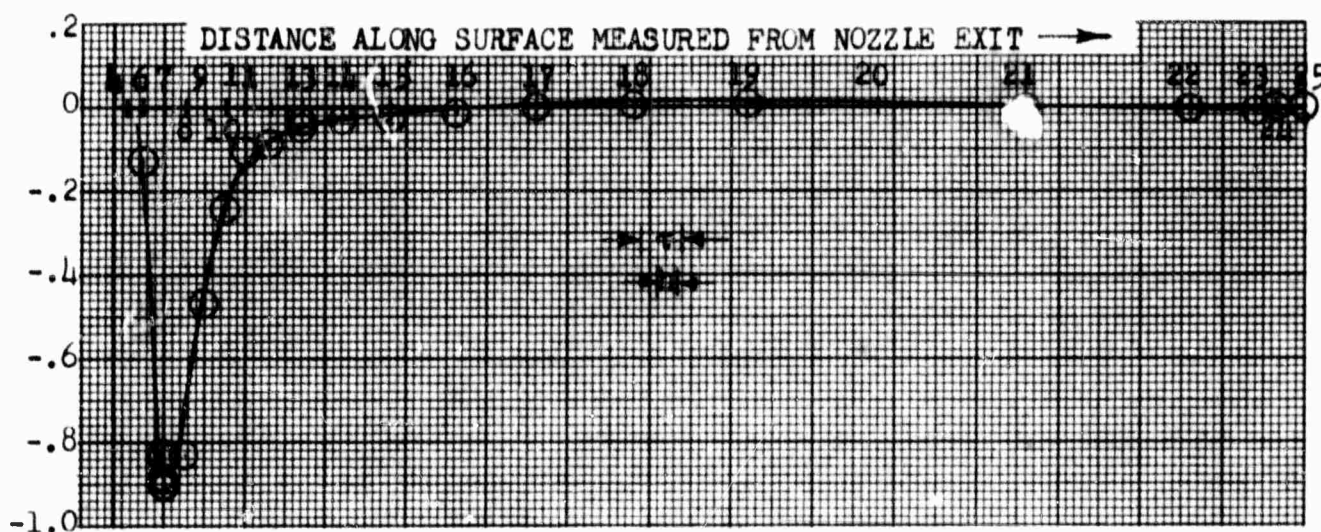


FIGURE 31:  SURFACE STATIC PRESSURE DISTRIBUTION FOR THREE-DIMENSIONAL
CONFIGURATION AT $\sigma = 2$, $P_{4_t} - P_o = 2.1$ in. Hg

32-2

32-4

32-1

32-3

FIGURE 32: FLOW VISUALIZATION PHOTOS OF THREE-DIMENSIONAL
EXTERNAL EJECTOR: $P_{4_t} - P_o = 11.0$, $\sigma = 1$ (next 3 pages )

32-6
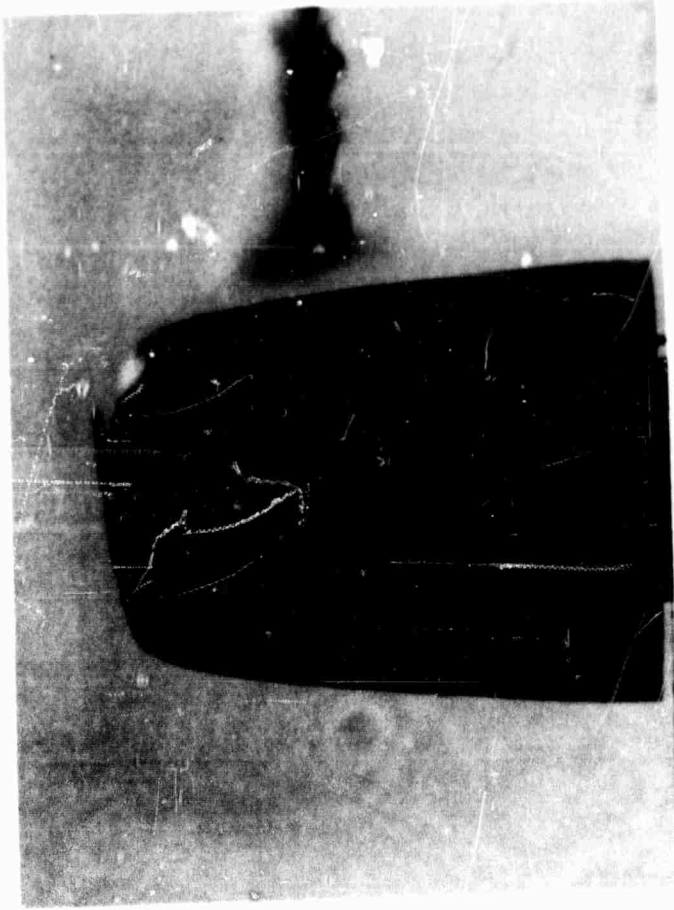
32-8

32-5
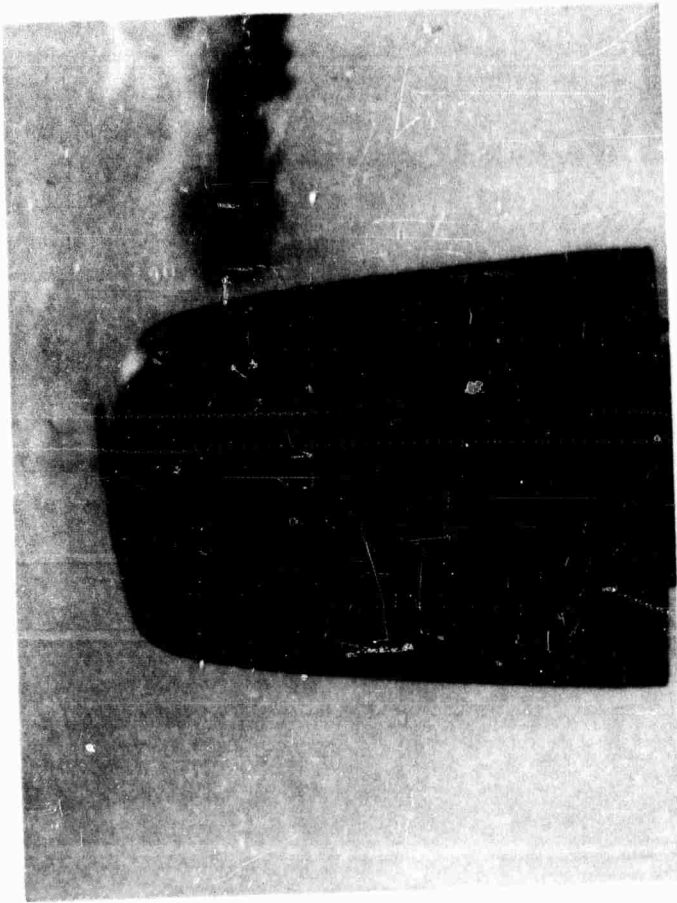
32-7
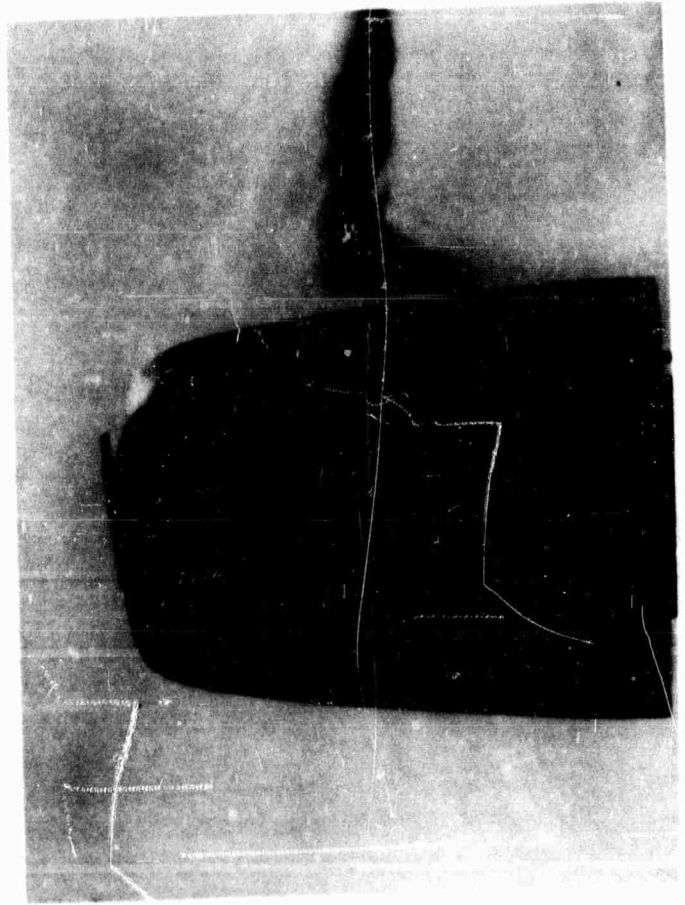
FIGURE 32: (continued)

32-10
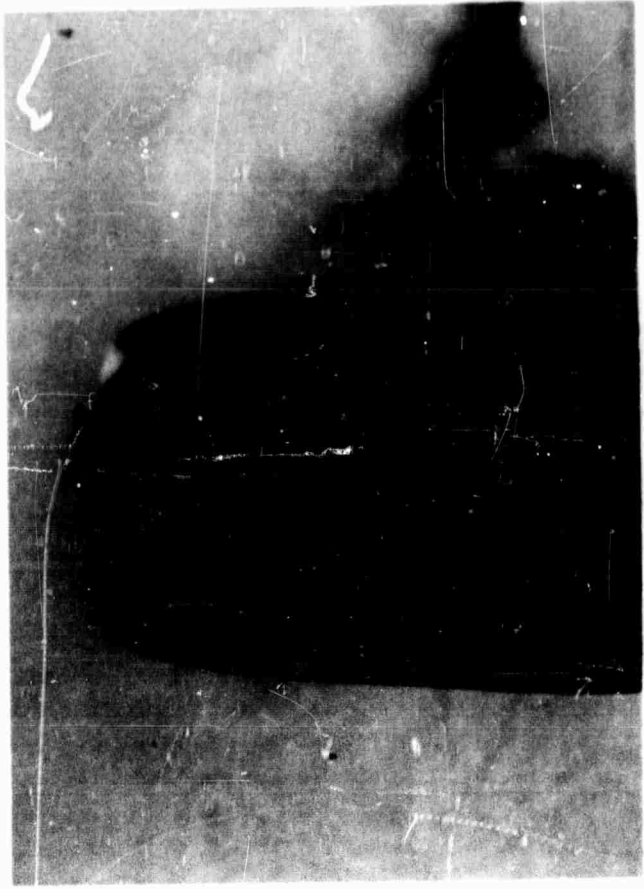
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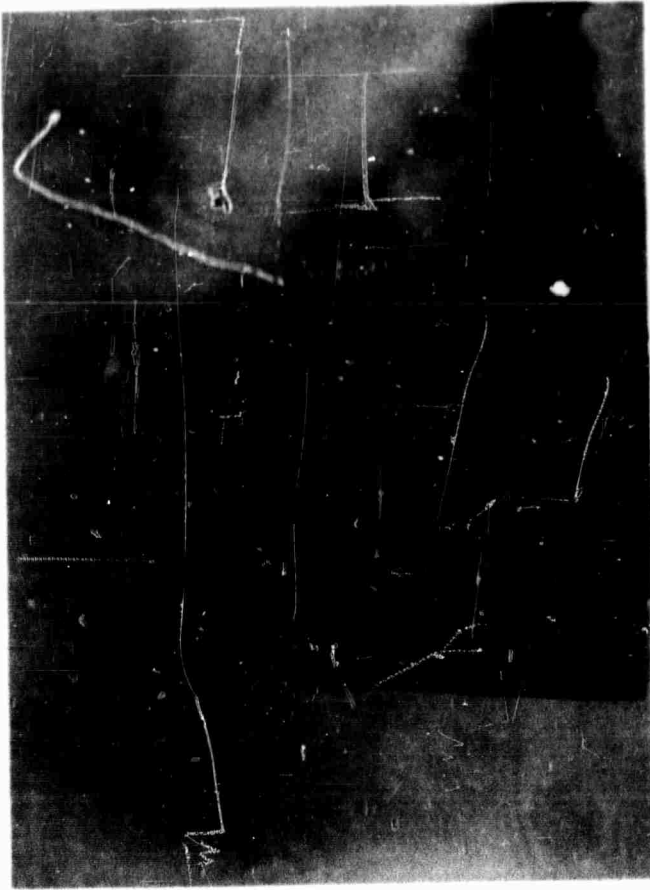
32-9
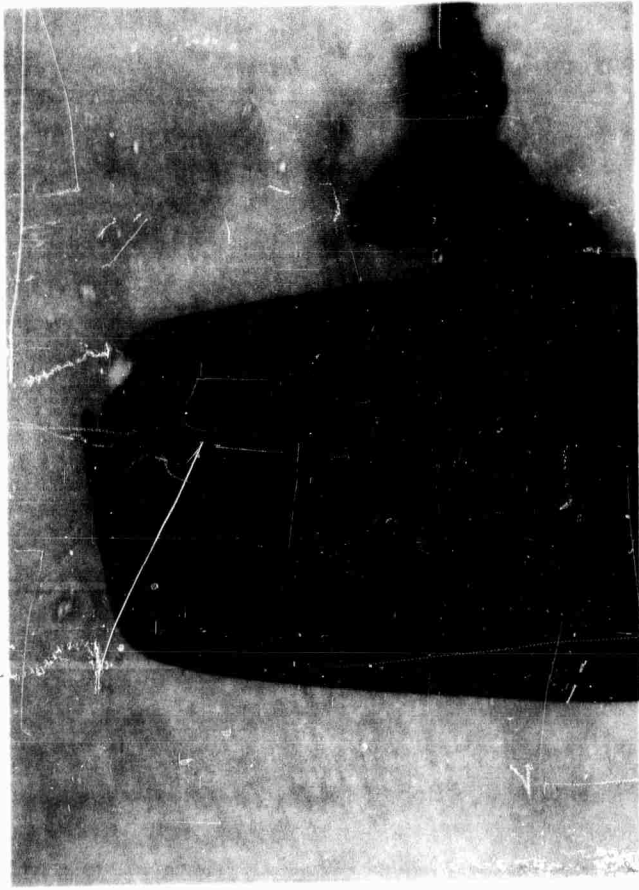
32-11
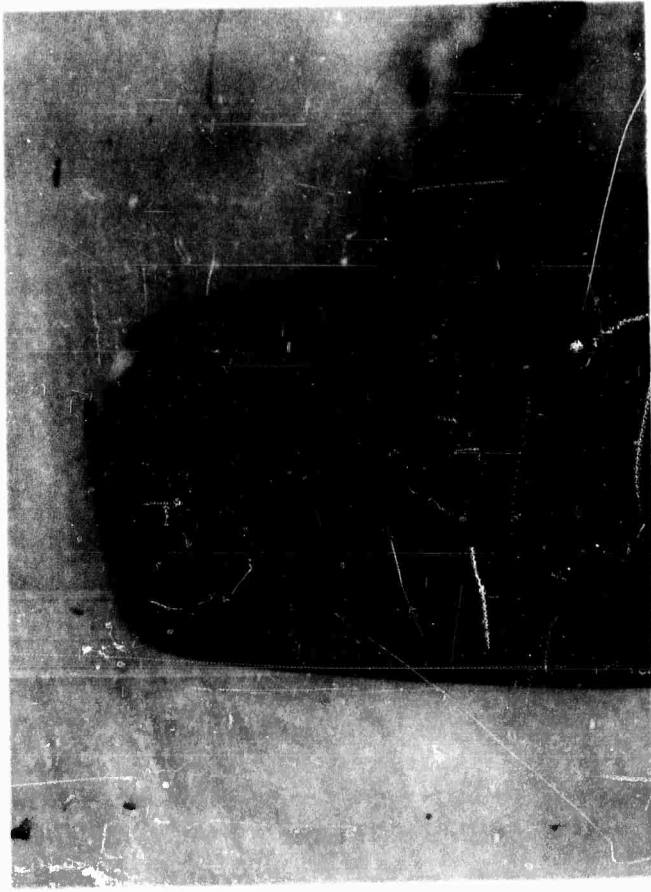
FIGURE 32: (continued)

32-14

32-16

32-13
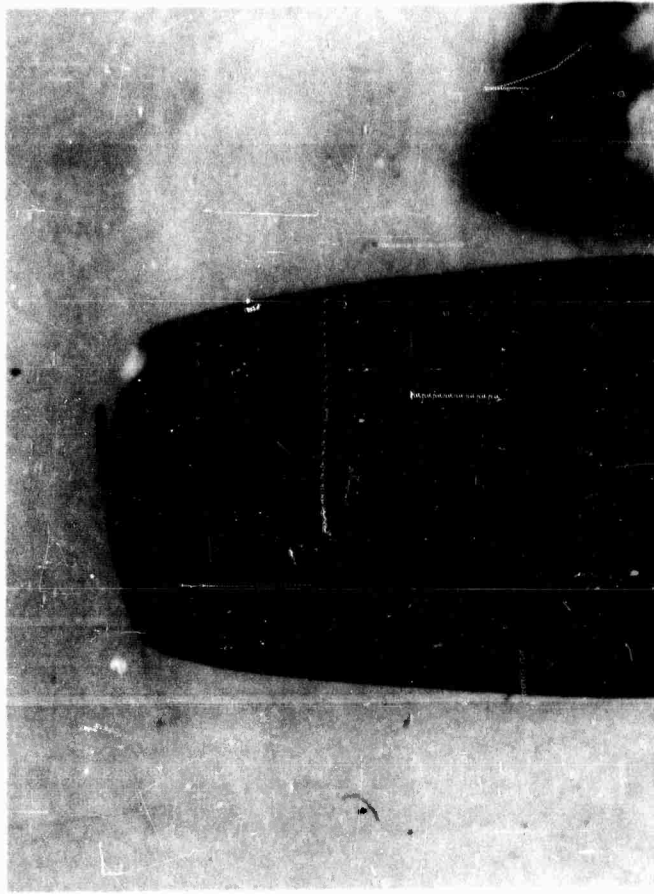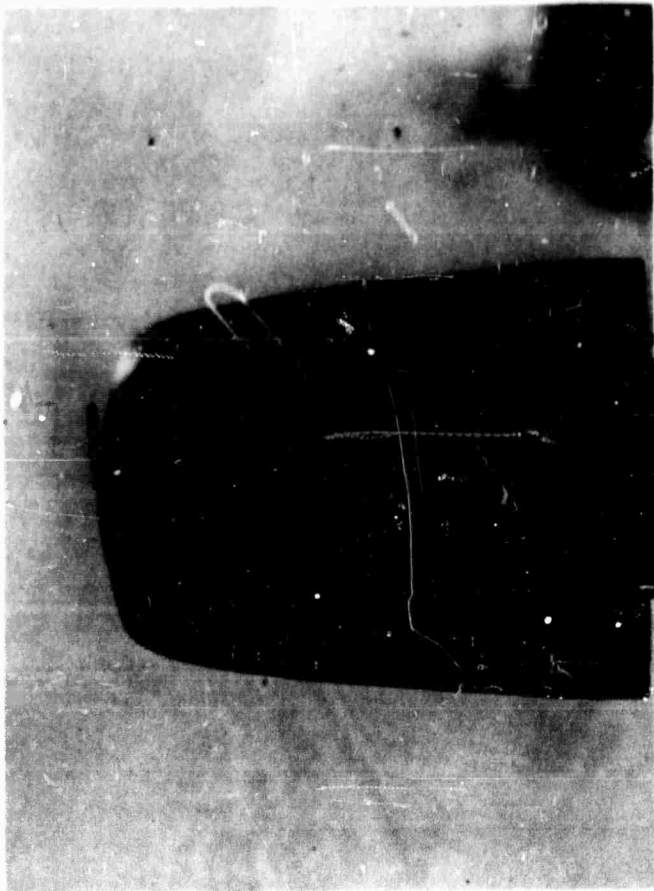
32-15
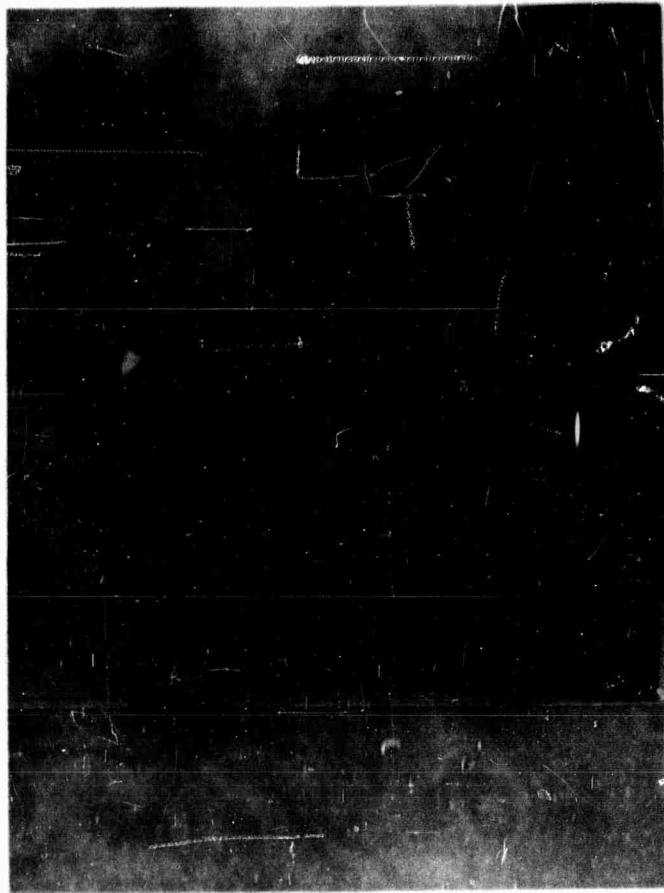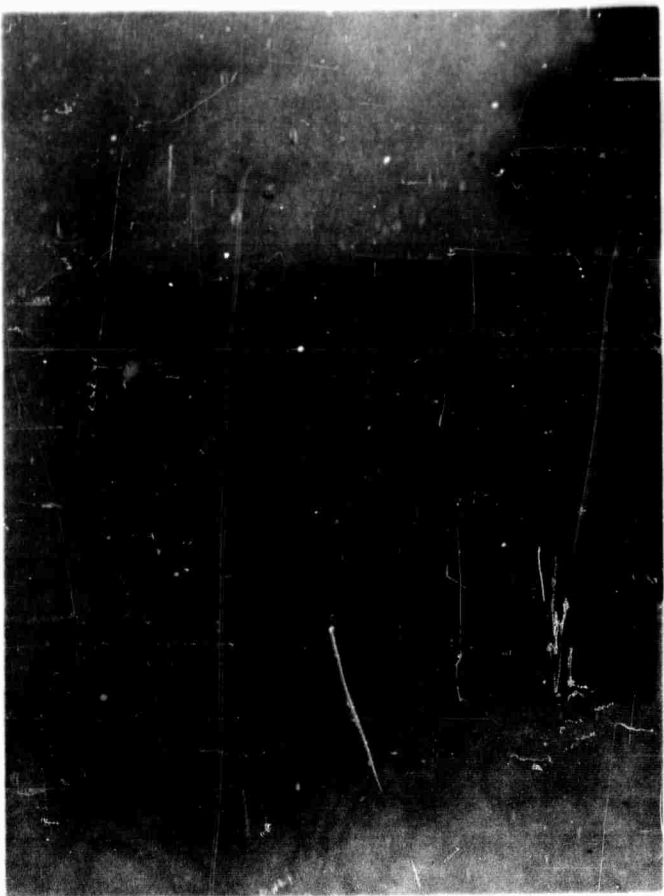
FIGURE 32: (continued)
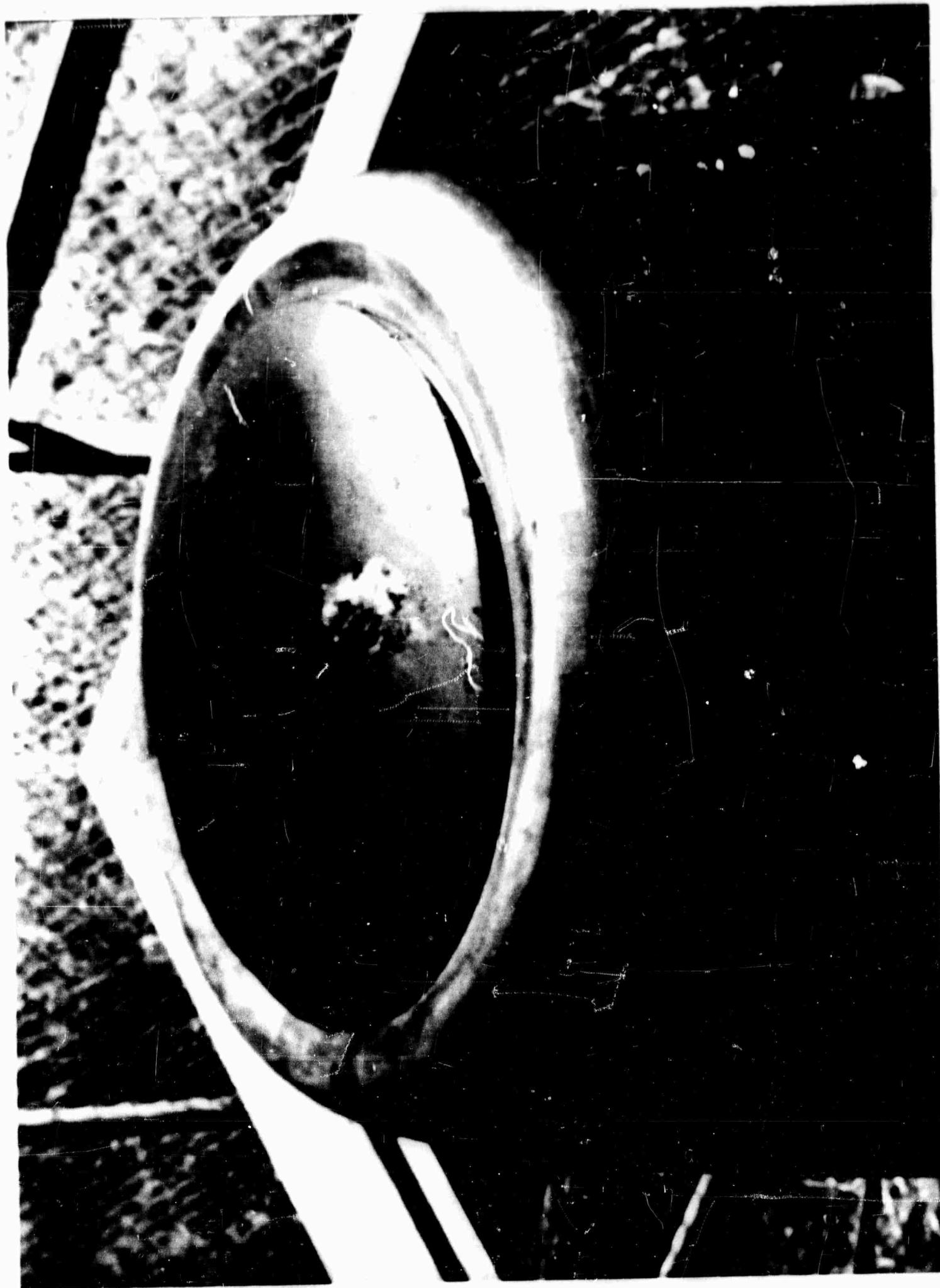
FIGURE 33: SMOKE TRACE, THREE-DIMENSIONAL EXTERNAL EJECTOR

Labels visible in the photograph:
- Two-dimensional External Ejector
- Radius Arm
- Flexible Joint
- Gimbal Ring
- Rigid Supply Duct
- Scales removed for another test program See Figure 35 for scale installation
- Flow Measuring Section

FIGURE 34: BASIC TEST STAND — TWO-DIMENSIONAL TESTS
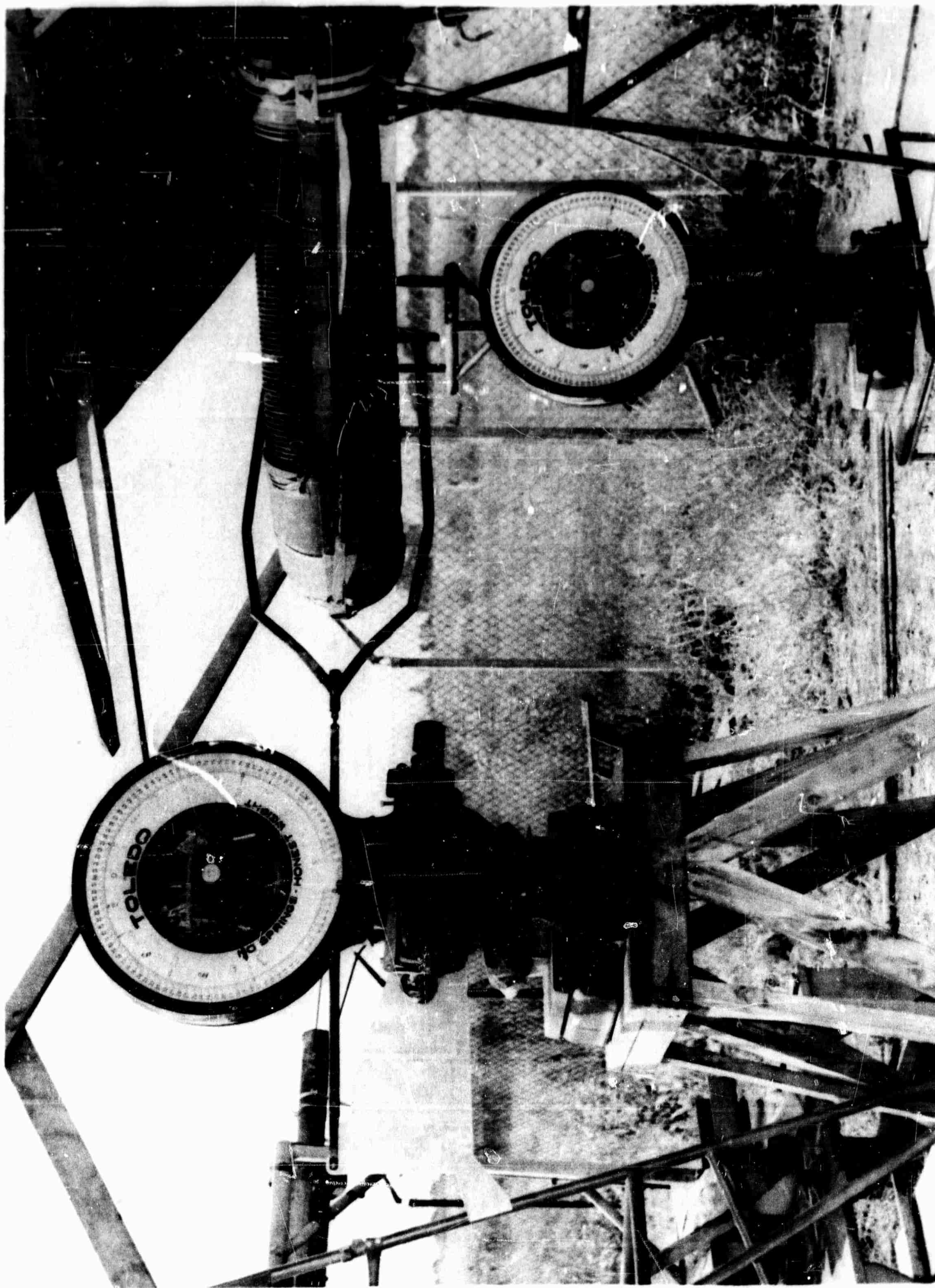
FIGURE 35: FORCE BALANCE FOR TWO-DIMENSIONAL TESTS
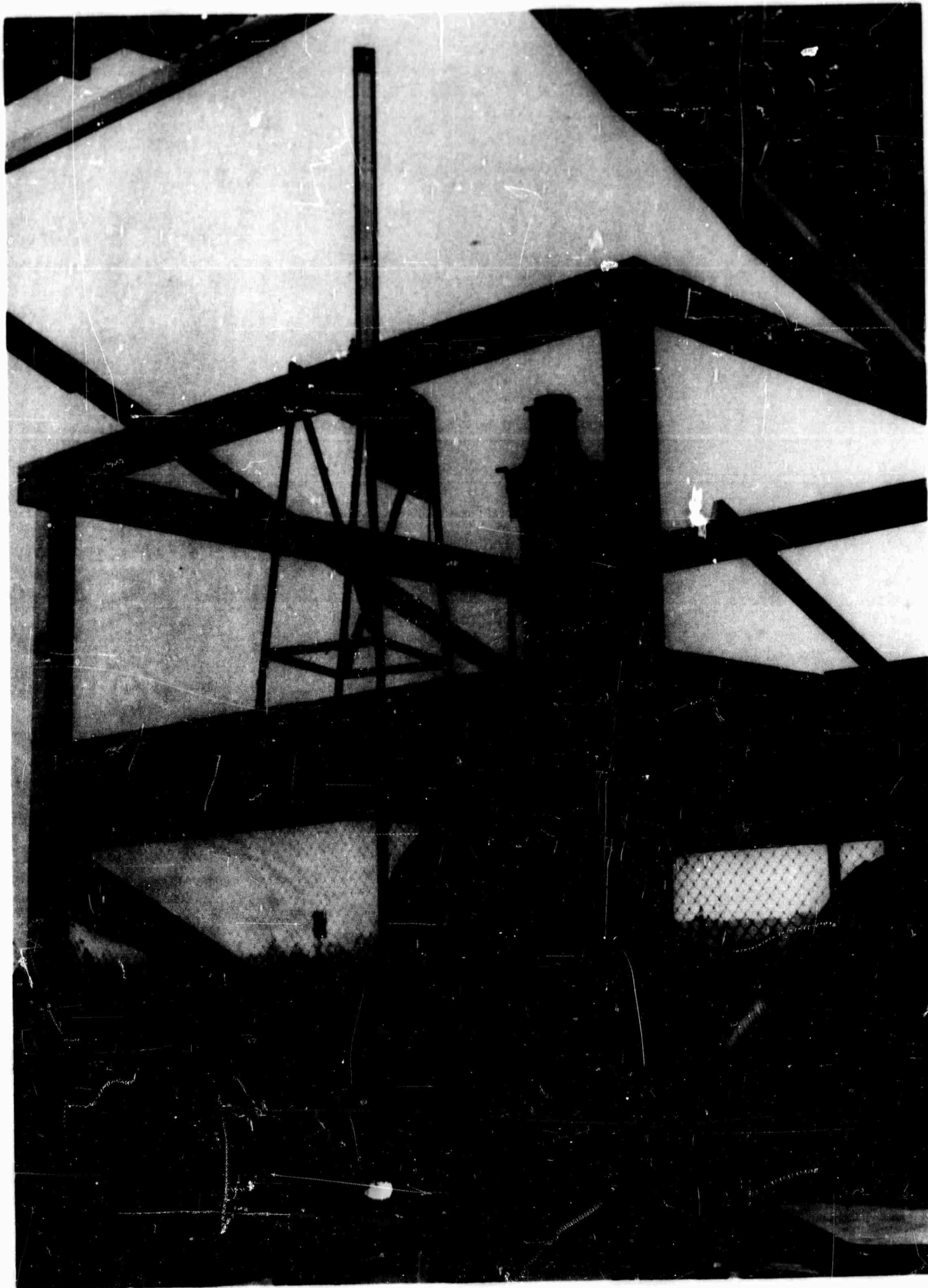
FIGURE 36: BASIC TEST STAND - THREE-DIMENSIONAL TESTS
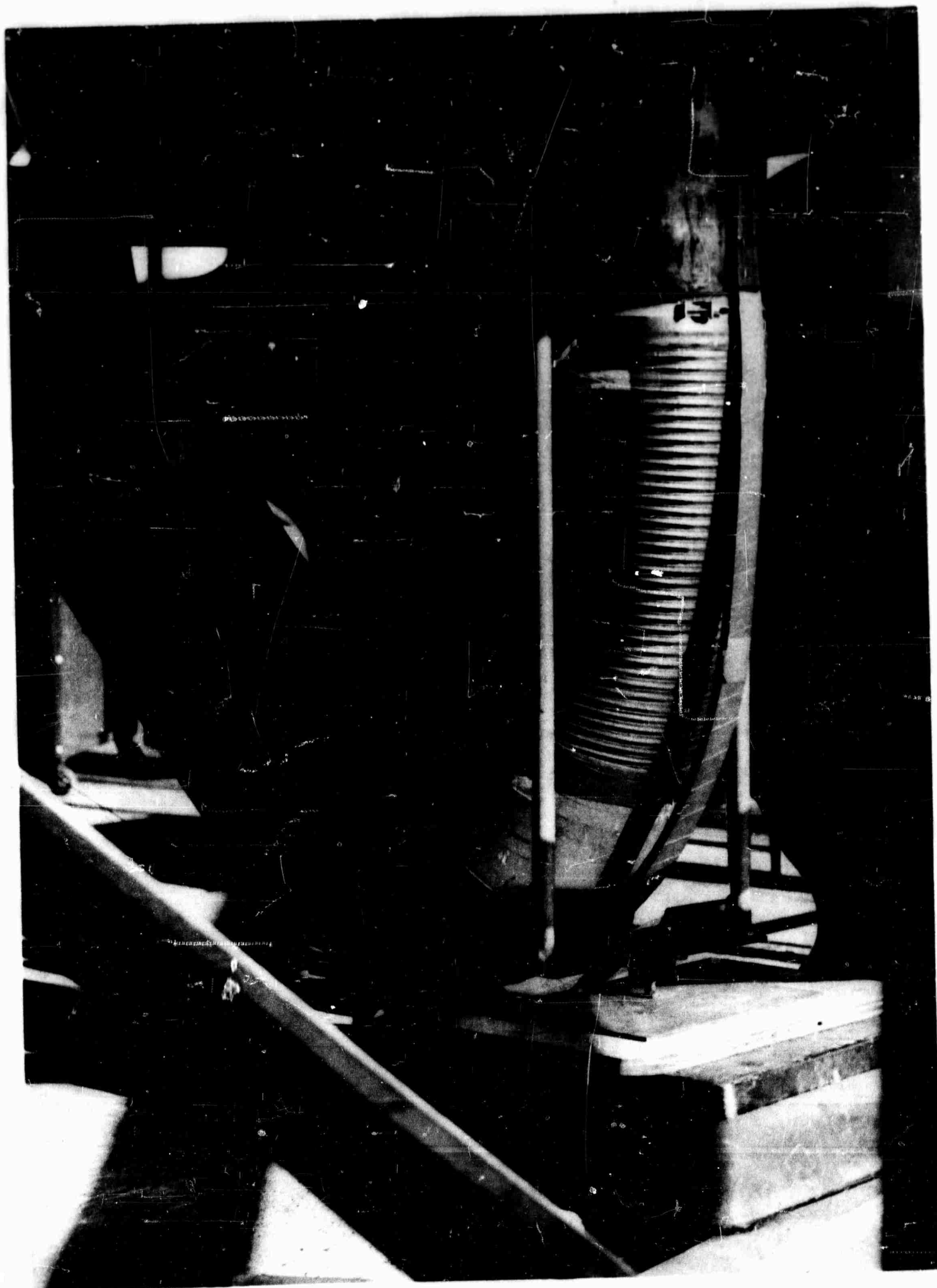
FIGURE 37:   FORCE BALANCE FOR THREE-DIMENSIONAL TESTS

ERROR IN VERTICAL REACTION, lb

SUPPLY PRESSURE, $P_{4_t} - P_o$ , in. Hg

two-dimensional configuration

three-dimensional configuration
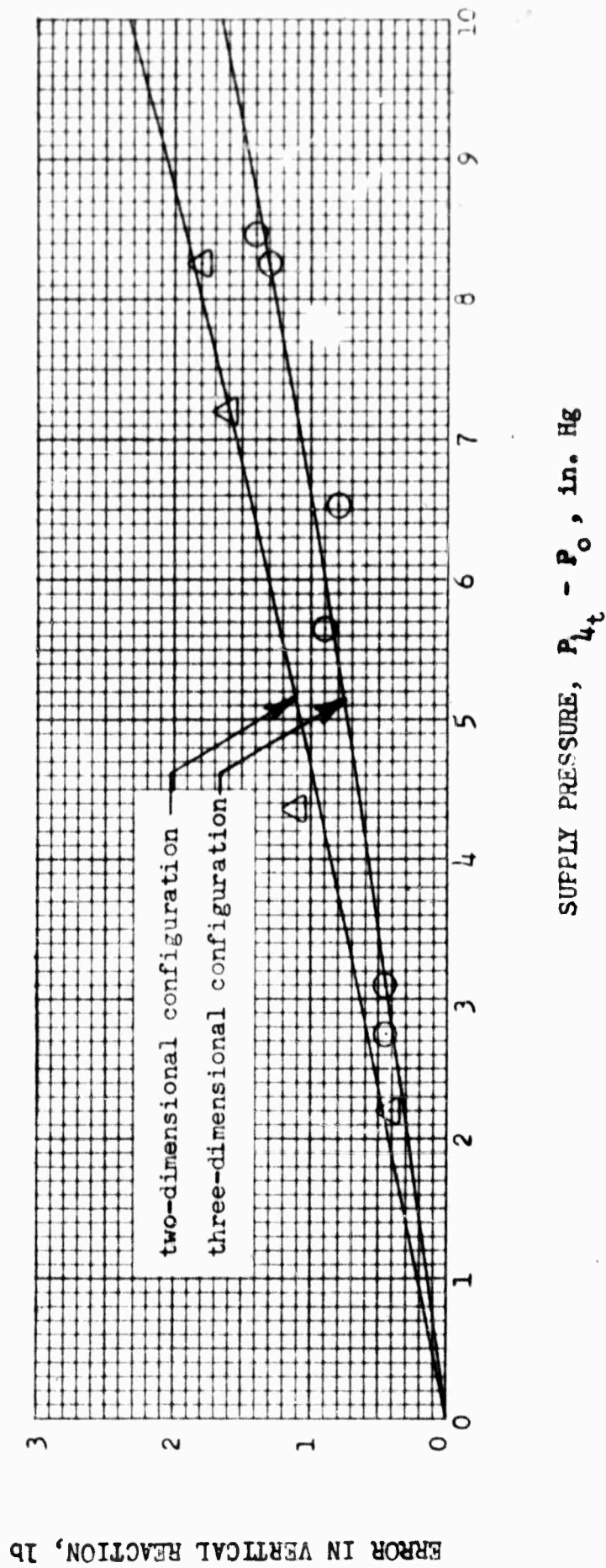
**Note:** no horizontal reaction error

FIGURE 38: TEST STAND STATIC CALIBRATION; NO FLOW
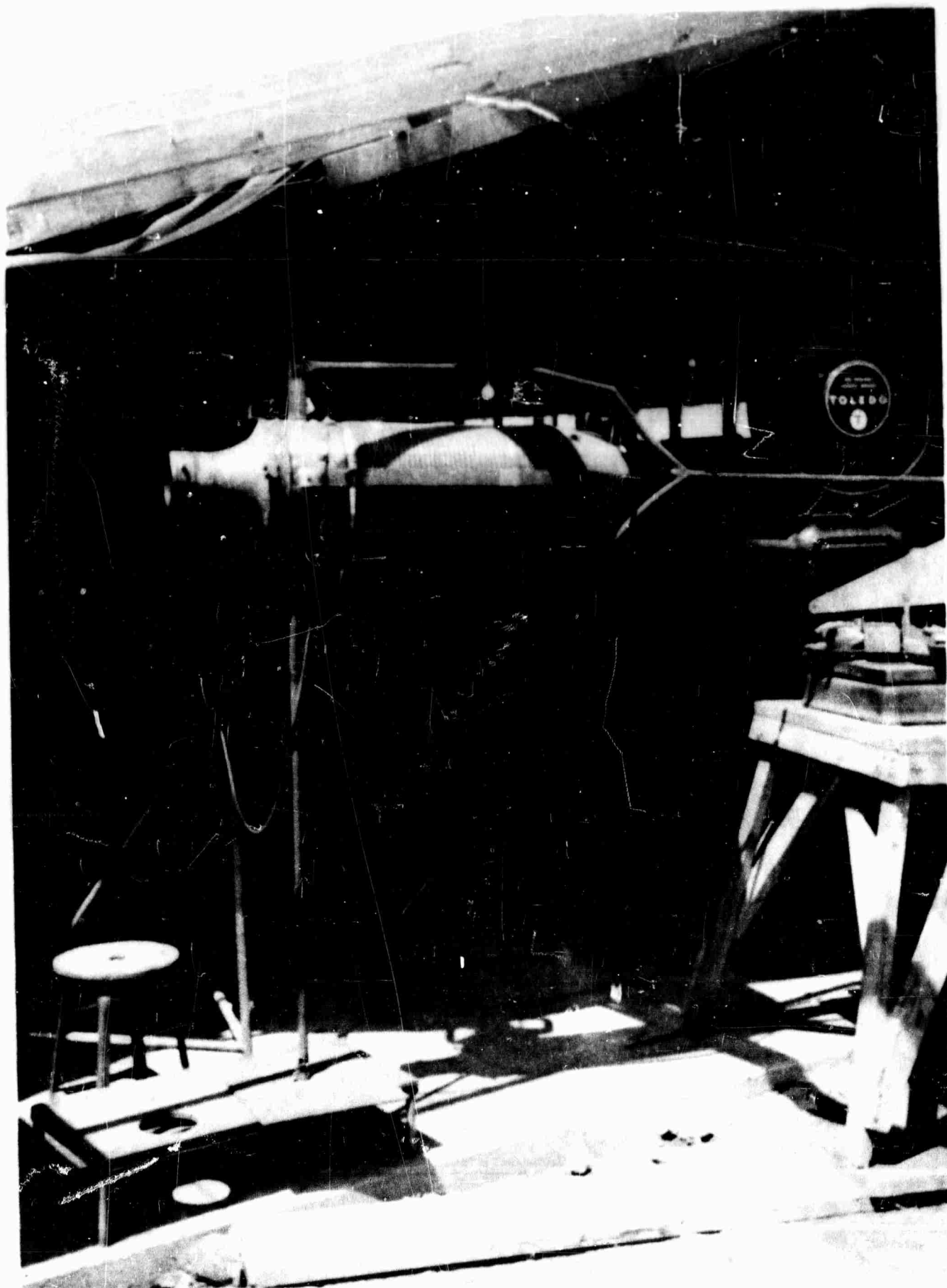
FIGURE 39:   INSTALLATION OF CALIBRATION NOZZLE; TWO-DIMENSIONAL TEST STAND
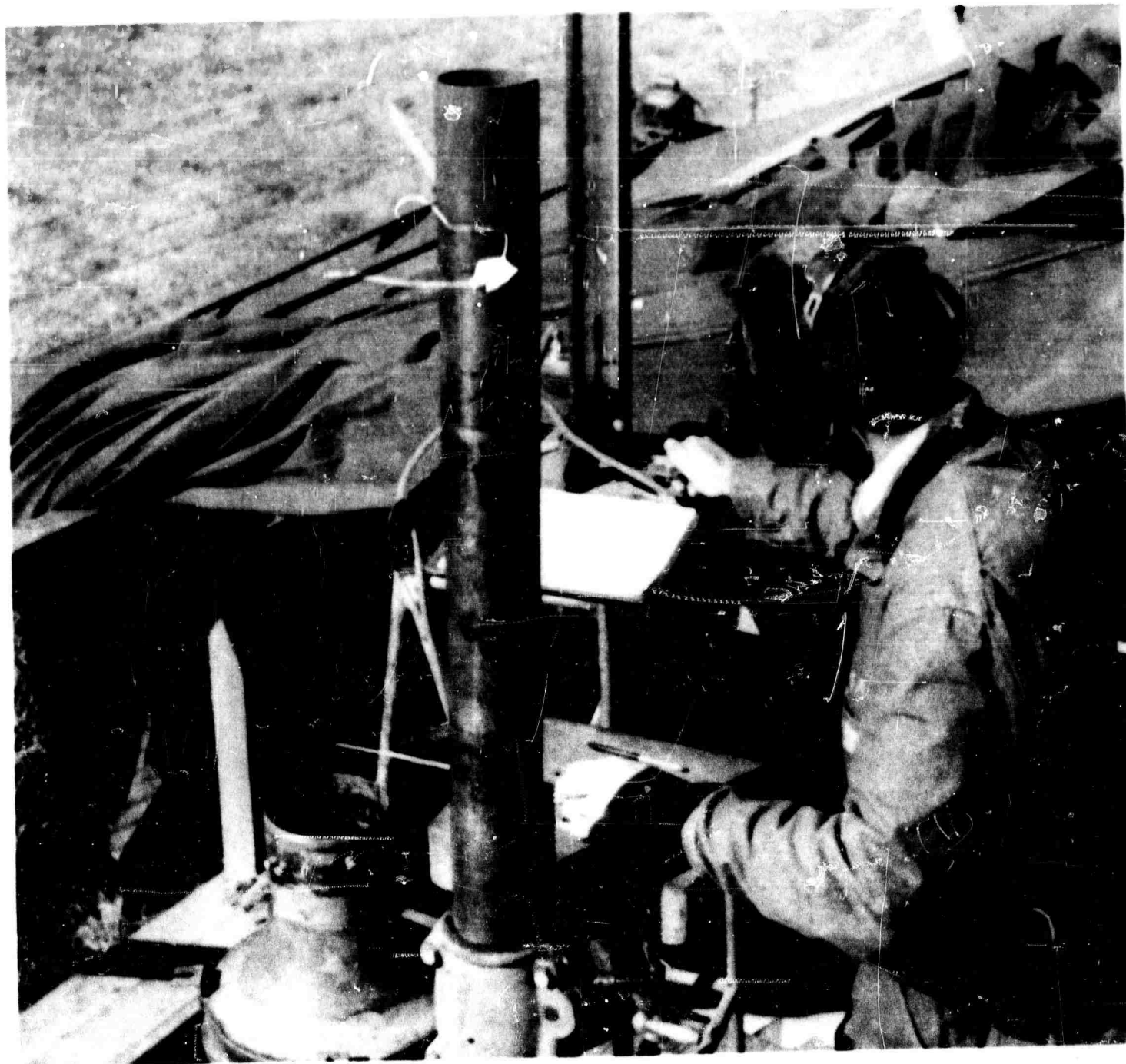
FIGURE 40:   PRESSURE SURVEY OF CALIBRATION NOZZLE; THREE-DIMENSIONAL TEST STAND
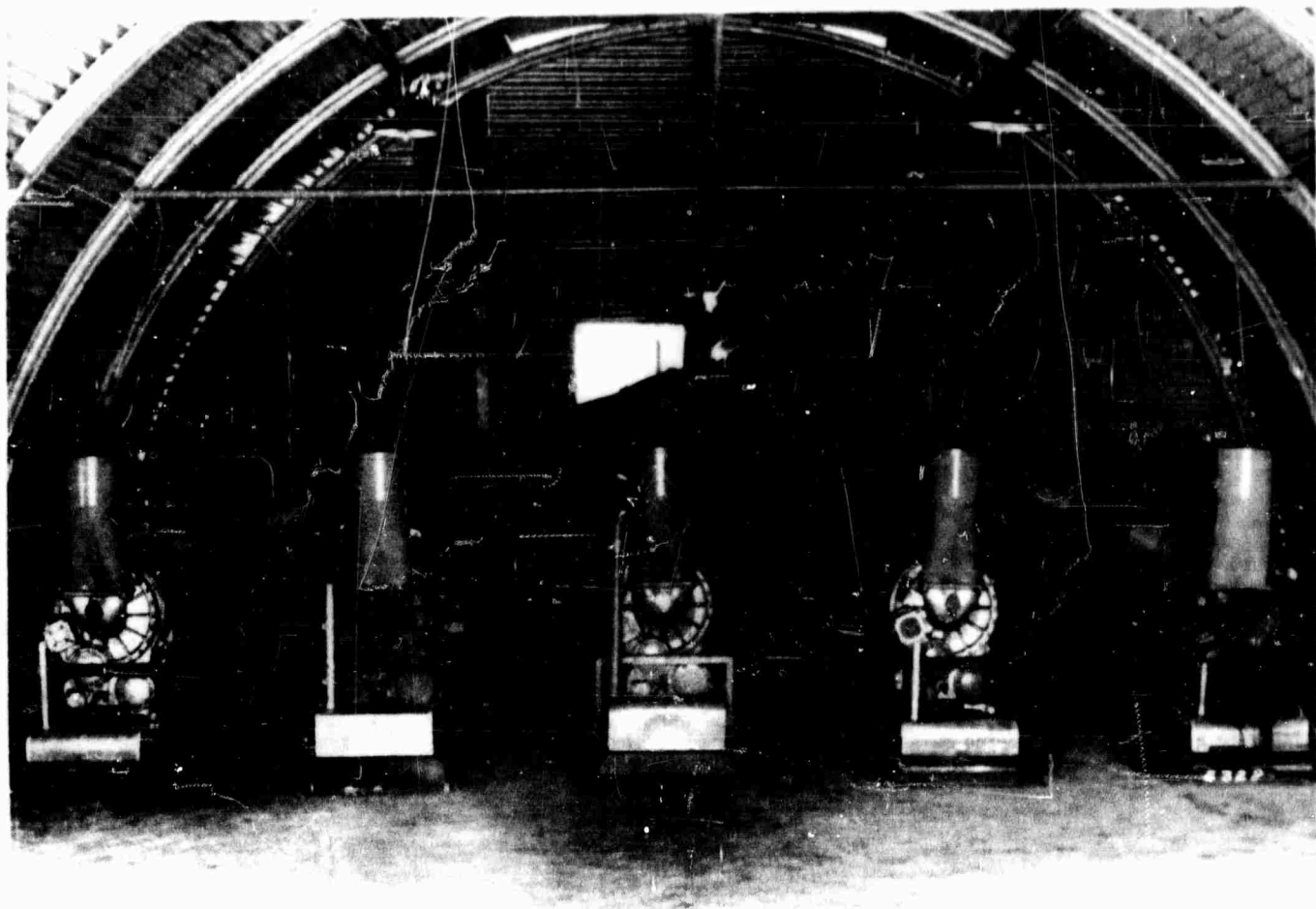
FIGURE 41:  AIR SUPPLY - BLOWER FACILITY

$\tau = .75$

ground plate
(centered under model)

$2\tau$

$80\tau$ (square)
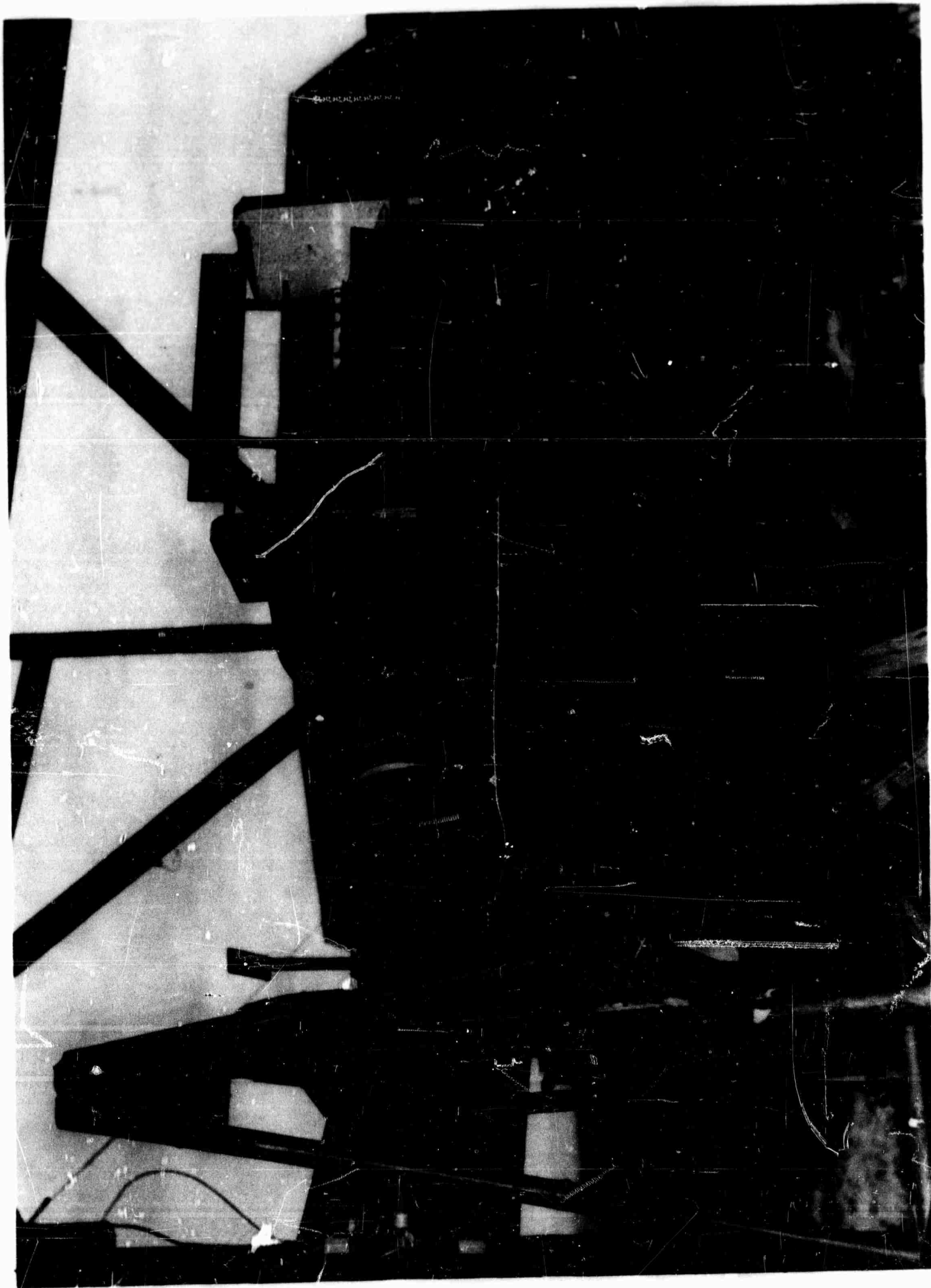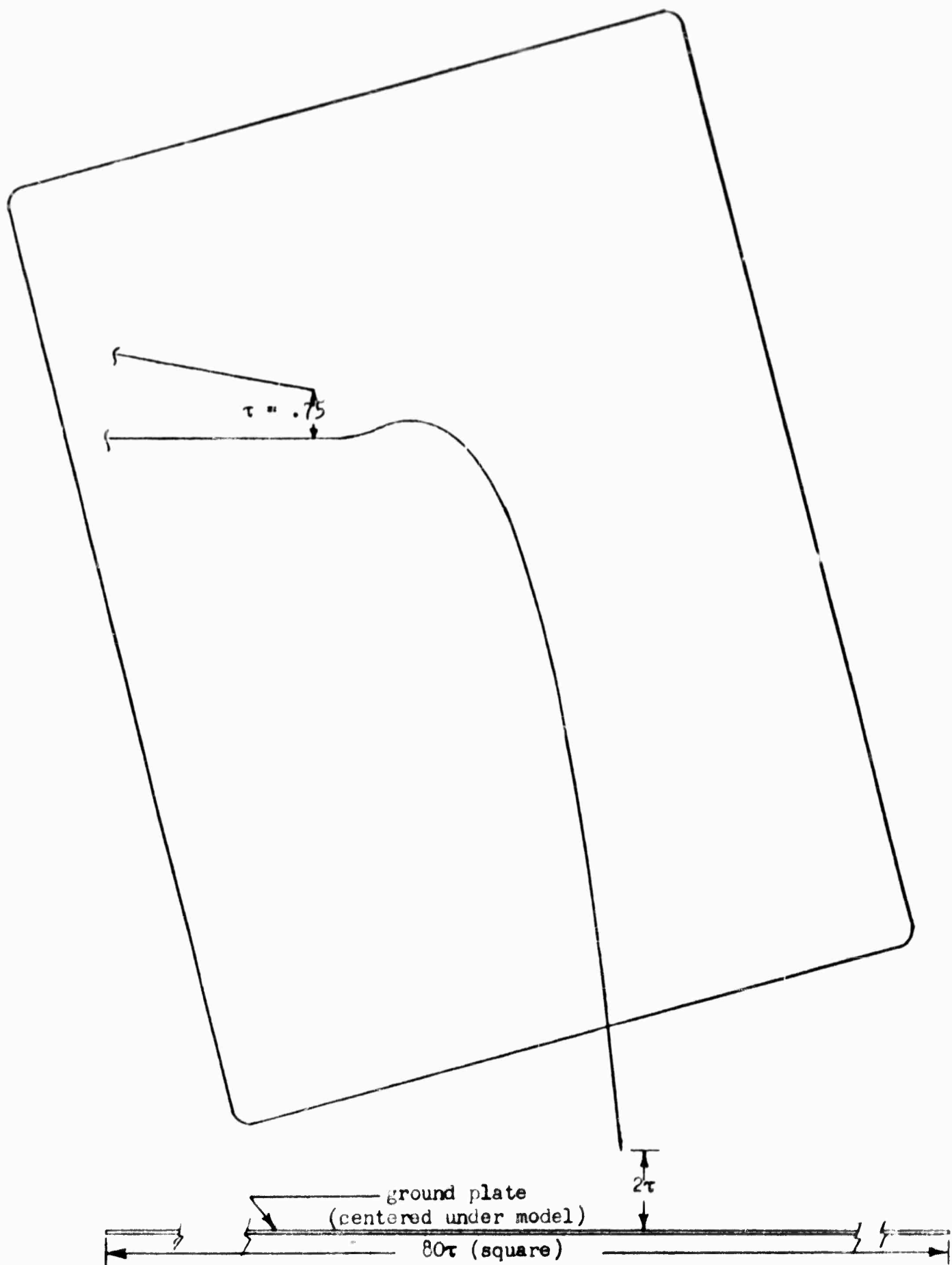
FIGURE 43: PERTINENT PARAMETERS - GROUND EFFECT TEST

## 7. APPENDICES

### 7.1 Appendix I - Test Set-Up and Procedures

The test fixture for the two-dimensional external flow ejector was de-
signed to permit direct, simultaneous measurement of forces in two normal
directions, and to eliminate the extraneous reaction that pressurization
of the 12-inch diameter air supply hose would have introduced into the
thrust measuring system. The test fixture for the three-dimensional ex-
ternal ejector measured force in the axial direction only. The fixtures
are shown in Figures 34, 35, 36, and 37.

The 20 foot long, torsionally rigid radius arm (Figure 34) was gimbaled
to the rigid air supply duct at one end to permit angular freedom in all
directions so that force measurements could be made by restraining the
arm movement with scales. The long arm effectively negates errors intro-
duced by restraining the arm movement at a point hat is not exactly co-
incident with the center of pressure on the model. The long arm also
reduces the restraining moment due to deflection of the flexible duct
joint at the gimbal. The model was mounted on the other end of the arm
and connected to the supply duct by the flexible 12-inch diameter hose.
The air supply hose was also secured to the radius arm just below the
gimbal. The only unrestrained length of hose was the length between the
rigid air supply duct and the point where the air hose was secured to the
radius arm immediately adjacent to the gimbal. In Figure 34 this unre-
strained section of hose (approximately 12 inches long) permitted movement
of t' imbal, and its alignment was adjustable so that extraneous reaction

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could be virtually eliminated from the system. The forces were measured with Toledo scales; the vertical force directly, the horizontal force through a bell crank linkage.

The pressure measurements were made with mercury manometers and critically calibrated airspeed indicators. Temperature measurements were made with a Rubicon potentiometer, Serial No. 59863, and copper-constantan thermocouples. Flow rate measurements were made with a calibrated ASME standard long-radius flow nozzle.

The test fixture force-measuring system was calibrated under "no-flow" conditions as it was set up for both the two- and three-dimensional cases. The results of this calibration in terms of indicated error as a function of corrected supply gage pressure is presented in Figure 38.

The flow section was calibrated by measuring the thrust and surveying the jet wake of a second standard long radius nozzle installed at the downstream end of the supply duct (model removed) as shown in Figures 39 and 40. Figure 40 shows the pressure traverse in progress.

The weight flow rate was computed from the pressure traverse data and the measured exit area of the nozzle. The pressure traverse was cross-checked by comparing the measured pressure recovery of the nozzle (nozzle efficiency or energy coefficient) and the measured thrust coefficient $\left(\dfrac{\text{measured thrust}}{\text{ideal thrust}}\right)$. (Thrust coefficient equals $\sqrt{\text{energy coefficient}}$ by definition.)

It is believed that the accuracy of the flow rate is within 3%, and the resultant lift within 1%.

The air supply system (Figure 41) used in these tests was constructed for development of the 8RJ2B Hiller ramjet engine which is used on the H-32 Hiller Hornet and Sally Rand helicopters. This system consists of five Allison 1720 supercharger compressors, each driven by a 150 HP Ford industrial engine. The discharge of the compressors is manifolded to the 12-inch diameter rigid supply duct.

The following measurements were made:

1. Vertical lift and horizontal thrust as appropriate.

2. Total pressure and temperature immediately upstream of external ejector.

3. Flow rate (inlet pressure, differential pressure, and upstream temperature relative to flow section) 24 diameters upstream of model.

4. Barometric pressure.

5. Relative humidity.

6. Static and total pressures.

7. Nozzle slot height, $\tau$, (at test pressure of run).

Prior to taking measurements at a specific pressure level, the system was operated until equilibrium temperature conditions were attained; the required readings were then manually recorded. Duplicate runs were made to verify the data.

All performance data was reduced to standard sea level conditions ($60^\circ$ F and 29.92 inches Hg) and also to one lb/second weight flow rate basis. The data reduction form $\dfrac{F_R}{\dot{w}\sqrt{\Theta_4}}$ is derived as follows:

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$$F = \frac{\dot{W}}{g}\triangle V$$

$$= \frac{\dot{W}}{g}V_5 \quad \text{when the approach velocity is zero or when}$$

total temperature and total pressure are used

to describe the approach (reservoir) conditions.

$V_5$ is taken at exit plane.

$$V_5 = (2gJ\triangle h)^{1/2} \quad \text{where} \quad h = \text{enthalpy}$$

$$= (2gJC_P\triangle T)^{1/2}$$

$$\triangle T = (T_{4_t} - T_o)$$

$$= T_{4_t}\left[1 - \frac{T_o}{T_{4_t}}\right] = T_{4_t}\left[1 - \left(\frac{P_o}{P_{4_t}}\right)^{\frac{\gamma-1}{\gamma}}\right]$$

$$V_5 = \left\{2gJC_P\, T_{4_t}\left[1 - \left(\frac{P_o}{P_{4_t}}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}^{1/2}$$

let .

$$T_{4_t} = \left(\frac{T_{4_t}}{T_{o_{SL}}}\right)T_{o_{SL}} = \theta_4\, T_{o_{SL}}$$

$$V_5 = \left\{2gJC_P\, \theta_4\, T_{o_{SL}}\left[1 - \left(\frac{P_o}{P_{4_t}}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}^{1/2}$$

$$\therefore \quad F = \dot{w}\left\{2gJC_P\, \theta\, T_{o_{ST}}\left[1 - \left(\frac{P_o}{P_{4_t}}\right)^{\frac{\gamma-1}{\gamma}}\right]\right\}^{1/2}$$

or

$$\frac{F}{\dot{w} \sqrt{\Theta_4}} = \left\{ 2gJC_P \, T_{o_{SL}} \left[ 1 - \left( \frac{P_o}{P_{4_t}} \right)^{\frac{\gamma-1}{\gamma}} \right] \right\}^{1/2}$$

This is the equation of the theoretical (isentropic) curve given in each performance figure. This derivation and method of reduction is appropriate for the performance of a converging nozzle and is a first approximation for the reduction of the performance of an ejector. As little ejector action is apparent here, the method is appropriate.

The plain rectangular nozzle was evaluated for comparison purposes. This evaluation was made both with and without side plates. It will be noted from the performance curves that there was little loss attributable to the side plates. Figure 42 shows rectangular nozzle set up for evaluation.

All tests were conducted out of ground effect except as noted. The ground effect tests were conducted by using a five-foot square piece of 3/4-inch plywood blocked up to give the desired ground clearance. The appropriate dimensions are shown in Figure 43.


7.2  Appendix II - Personal Discussions

Between 9 and 14 June 1958, the writer travelled through the East and Midwest to discuss the possibility of obtaining thrust augmentation through the use of the external ejector. Both current and past investigators were contacted: Mr. Uwe H. von Glahn, Lewis Flight Propulsion Laboratory (NACA) where work was completed just over a year ago; Drs. Markstein and Rudinger,

at Cornell Aeronautical Laboratory, who were associated with the 1952 Coanda work there; Mr. J. C. M. Frost, Mr. Desmond Earl, and Mr. Don Whittley, whose work at Avro Aircraft Limited, Malton, Ontario, is currently in progress; and Drs. Foa and Yen at Rensselaer Polytechnic Institute.

Mr. von Glahn's investigation covered single flat plate deflection surfaces, curved surfaces, and multiple flat plate surfaces, all two-dimensional. The single flat plate work is reported in Reference 29. The remainder will be covered in a second report to be published in the next few months. Reference 28 briefly discusses curved surfaces and multiple flat plate surfaces.

His interest in the external ejector is as a turning device rather than as a thrust augmenter. He had not anticipated any augmentation and does not consider it possible in a $90^\circ$ turn. His efforts were directed toward determining a surface which would give an optimum (maximum negative) pressure distribution. No pseudo-ejector reasoning was evident in his work; that is, he made no attempts to improve the mixing between the primary jet and ambient air.

His unpublished data for $90^\circ$ turns indicates a maximum value of 0.89 for the ratio of lift-to-undeflected-jet thrust (real thrust ratio). This was attained with a model which had nine flat segments. The maximum performance he achieved with a continuously curved surface was a ratio of 0.85. We have achieved a corresponding value of 0.90 with the Foa-Cornell Aeronautical Laboratory two-dimensional curved surface, equivalent to a ratio of lift-to-isentropic thrust of 0.88 (ideal thrust ratio).

Mr. von Glahn displayed two curves which will be published in his second
report. One curve summarized his pertinent external ejector nozzle per-
formance data; the other presented the pressure distribution for a typical
curved-surface NACA model. The model consisted of a converging nozzle
followed by a $6^o$ deflected flat surface approximately 0.10 $\tau$ long, which
in turn was followed by a constant-radius surface, with the radius equal
to $\tau$ and tangent to the end of the flat surface. (The purpose of the
initial deflected flat surface was to eliminate positive pressure gradients
at the nozzle exit which he claimed existed with a constant radius surface
tangent to one wall of the nozzle at the nozzle exit.) The pressure dis-
tribution was very irregular and difficult to understand.

The test setup was such that it was necessary to determine a c.p. location
from the observed pressure distribution in order to reduce the measured
reactions for the lift developed by the model.

Mr. von Glahn said that he believed a performance figure of 0.95 (real
thrust ratio) was possible with further development, but added that the
surfaces required (based on his pressure distribution) might be quite
impractical.

The purpose of visiting Cornell Aeronautical Laboratory (C.A.L.) was to
attempt to determine the cause for the great discrepancy between their
two-dimensional work and ours with a surface of identical shape but
larger scale. Discussions with Dr. Markstein and Dr. Rudinger estab-
lished that they were only very loosely associated with the original
Cornell Aeronautical Laboratory work.

Dr. Rudinger, who has been connected with the fluid dynamics portion of Project SQUID for many years, searched his files for further information on the Cornell Aeronautical Laboratory external ejector work to no avail, with the exception of one photograph.

These two gentlemen did not feel that there was any basis on which to expect augmentation from an external ejector.

Dr. Logan, the original external ejector investigator at Cornell Aeronautical Laboratory, had visited Drs. Markstein and Rudinger in the morning just prior to this interview. They quizzed him briefly regarding his work in 1952, but he was unable to offer any further suggestions.

At Avro Aircraft, Ltd., in Malton, Ontario, discussions were held with Mr. J. C. M. Frost, Chief Design Engineer, Special Projects Group; Mr. Desmond Earl, Chief Aerodynamicist, Special Projects Group; and Mr. Don Whittley, Aerodynamicist. They indicated that their preliminary work resulted in lift-to-isentropic-thrust ratios of from 0.85 to 0.90. They did not specify the exact surface parameters involved, but implied that it was a simple circular arc. They displayed one curve of pressure distribution with the model sketched on it, which showed the surface to be a simple arc of radius approximately equal to nozzle height. The nozzle aspect ratio is unknown. The pressure distribution was smooth, as would be expected from our work, and not irregular; nor was there a positive gradient as was predicted by von Glahn. When they were questioned on the effect of nozzle aspect ratio, they said that it was believed to be important.

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They went on to say that they had reduced aspect ratio on one model to the point where the flow would no longer cling. Their work is continuing at an increasing rate in their attempt to improve the performance of the external ejector. They stated that they were just starting their "serious testing" of the phenomenon.

Mr. Frost stated that they had given up any idea of obtaining thrust augmentation out of the unshrouded nozzle, and are using it only as a turning device. They feel that it would be necessary to use additional surfaces for the secondary air to act upon and to provide an area of low pressure mixing in order to realize any thrust augmentation. These additional surfaces would essentially convert the nozzle to an internal flow type ejector.

Dr. Foa, Professor of Aeronautical Engineering, Rensselaer Polytechnic Institute, was in charge of the 1952 external ejector work at Cornell Aeronautical Laboratory (his previous employment). Dr. Yen, also Professor of Aeronautical Engineering at Rensselaer, has written several reports on his analytical Coanda investigations.

Dr. Foa was unable to offer any reason why our two-dimensional results did not equal his and Logan's Cornell Aeronautical Laboratory results. He did admit that there was room for error in their two-dimensional performance values. He considered their three-dimensional work at Cornell Aeronautical Laboratory, however, to be very good. This work indicated an augmentation of 50%. When told of Schubauer's negative results with

a similar three-dimensional device, he remarked that Schubauer was a good experimenter, but it did not reduce his confidence in his and Logan's previous three-dimensional work at Cornell Aeronautical Laboratory. Of all the people contacted, only Drs. Foa and Yen indicated any hope for augmentation by use of the external ejector.

## 7.3  Appendix III - Chronological Review of Selected Literature

In the attempt to determine why our results had not shown thrust augmentation, several additional references were discovered and reviewed; some of these will be discussed here, and all will be listed in the bibliography. Metral and Zerner (Reference 12) report the work of M. Lafay in 1918 in connection with the so-called Chilowsky effect. Quoting M. Lafay, M. Chilowsky had the notion of "decreasing the resistance opposed by the air to a projectile by providing them in front with a sort of beak which emits transversely, through a circular orifice, a sheet of fire". This was modified by M. Lafay by reducing the length of the beak to zero. M. Lafay's best result was to reduce the initial drag to 1/2 by this means. There is no indication of the input required. Schubauer (Reference 16) conducted tests in 1933 with the external ejector incorporated in the nose of a dirigible configuration. His results indicated that a thrust loss was realized when compared to a nozzle in the tail of the dirigible configuration.

R. S. Sproule, and S. T. Robinson (Reference 17) in 1944 report on their interrogation of Coanda. Geometric data is given, as are performance

curves (data supplied by Coanda). This data shows augmentation ratios as high 2.7 for an internal ejector. Sketches depicting several ideas for annular external ejectors in conjunction with turbojet engines are shown. No performance data is given for the external ejector. Sproule says Professor Zerner was one of Coanda's chief scientific aides before the war but seemed to have lost interest and considered the exhaust silencer study as the most important work done. Voedisch (Reference 3) in his 1947 report, which was quoted previously, seems to have summed up the situation quite well. (See page 6 .)

L. J. Boyer (Reference 4) in 1948 under Dr. M. J. Zucrow's direction per-formed the first known well-instrumented experimental evaluation of the external ejector in this country using a single flat deflection surface. His work was concerned primarily with a study of the reduction of the pressure in the nozzle exit and increase of the mass flow of the jet. Optimum values for surface deflection related to "overhang" were obtained. Boyer noted that the flap deflection force was greatest just prior to breakaway. Marwood's work (Reference 5) in 1949 at Purdue continued and expanded Boyer's work and is discussed in the introduction. (See page 3 .)

Young and Zonars' work (Reference 18) at Air Materiel Command evaluated an original "Coanda nozzle" (internal flow) and the "Coanda wing" (external flow). The evaluation of the wing device is analogous to our evaluation of the external ejector as far as the flow phenomenon involved is con-cerned. However, the data obtained is difficult to use. It is stated that the wing drag was reduced by use of this phenomenon, but it is also noted

that other means of boundary layer control are more effective.

Foa and Logan's work at Cornell Aeronautical Laboratory (Reference 6) in 1952, in an attempt to improve the backflow out of the valveless pulsejet inlet (i. e., to convert it to useful thrust), led them to a study of clinging flow. One of their initial tests with a three-dimensional configuration indicated an augmentation ratio of 1.5. They then went to the two-dimensional configuration in order to facilitate study of the problem. As mentioned previously in this report, they evaluated two families of profiles. Data for both are presented which indicate a maximum augmentation ratio of 1.72 when the thrust of the deflected jet is compared to the thrust of the free jet with side plate, and a ratio of 1.05 when compared to the free jet without sideplates.

Metral's first published work (Reference 7) in 1939, which is the first theoretical work on this phenomenon, dealt primarily with the "pressure reduction in the slot". Metral and Zerner published a paper, (Reference 12) in 1953 which also dealt with application to silencers and flow augmenters (i. e., internal flow devices). They point out that the measurement of the "Coanda nozzle" performance was not very precise while quoting augmentation ratios of 1.5 to 2. The "Coanda wing" is also discussed. No augmentation figures are given for the external ejector.

B. S. Stratford (Reference 15) has shown theoretically that augmentation is possible if mixing takes place at a low pressure. However, his model tests indicate no augmentation. In fact, a loss of 25% was noted in the static

case. He reasons that this is caused by secondary effects such as back-flow and energy loss with primary air impingement on the surface. Stratford ignores temperature effects in the analysis.

P. R. Payne points out this omission in his paper (Reference 19) saying that Stratford's equation is correct only for a cold jet. Payne's curves show that the theoretically possible augmentation is considerably less than that calculated by B. S. Stratford when the jet temperature is con-sidered. He comments that even though the theory indicates possible thrust increase, it can not be realized because the low pressure generated by the acceleration of the secondary air has no surface on which to act. That is, the secondary duct is required.

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North American Aviation, Inc.                                         1
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